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## (54) Plasma reactor with heated source of a polymer-hardening precursor material

(57) A general method of the invention is to provide a polymer-hardening precursor piece (such as silicon, carbon, silicon carbide or silicon nitride, but preferably silicon) within the reactor chamber during an etch process with a fluoro-carbon or fluoro-hydrocarbon gas, and to heat the polymer-hardening precursor piece above the polymerization temperature sufficiently to achieve a

desired increase in oxide-to-silicon etch selectivity. Generally, this polymer-hardening precursor or silicon piece may be an integral part of the reactor chamber walls and/or ceiling or a separate, expendable and quickly removable piece, and the heating/cooling apparatus may be of any suitable type including apparatus which conductively or remotely heats the silicon piece.



European Patent  
Office

## EUROPEAN SEARCH REPORT

Application Number

EP 97 30 3170

DOCUMENTS CONSIDERED TO BE RELEVANT		Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.CI 6)		
Category	Citation of document with indication where appropriate of relevant passages				
X	EP 0 601 468 A (APPLIED MATERIALS INC)	1.11, 33-35, 40.41	H01J37/32		
Y	* page 3, line 11 - line 18 *	7.8.21, 22.37, 68.69			
A	* page 3, line 40 - page 4, line 16 *	5.6.9, 23, 27-29, 38.42-44			
Y	EP 0 552 491 A (APPLIED MATERIALS INC)	7.8.21, 22.37, 68.69			
	* page 10, line 24 - line 32 *				
	* page 19, line 39 - line 47 *				
	* page 20, line 3 - line 17 *				
	* page 21, line 7 - line 18 *				
A	EP 0 651 434 A (APPLIED MATERIALS INC)	3.13, 70-74	TECHNICAL FIELDS SEARCHED (Int.CI 6)		
	* the whole document *	---	H01J		
A	EP 0 552 490 A (APPLIED MATERIALS INC)	17	H01L		
	* column 3, line 22 - line 33 *	---	C23F		
A	DATABASE WPI Section Ch. Week 8715 Derwent Publications Ltd., London, GB; Class A14, AN 87-105079 XP002047813 & JP 62 052 714 A (OLYMPUS OPTICAL CO LTD) 7 March 1987 * abstract *	11.15			
A	US 5 258 824 A (CARLSON DAVID K ET AL)	30.45			
	* column 1, line 33 - line 59 *				
	* column 3, line 21 - line 34 *	---			
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The present search report has been drawn up for all claims					
Place of search	Date of completion of the search	Examiner			
THE HAGUE	21 November 1997	Capostagno, E			
CATEGORY OF CITED DOCUMENTS					
X	particularly relevant if taken alone				
Y	particularly relevant * combined with another document of the same category				
A	technological background				
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	* theory or principle underlying the invention				
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	D document cited in the application				
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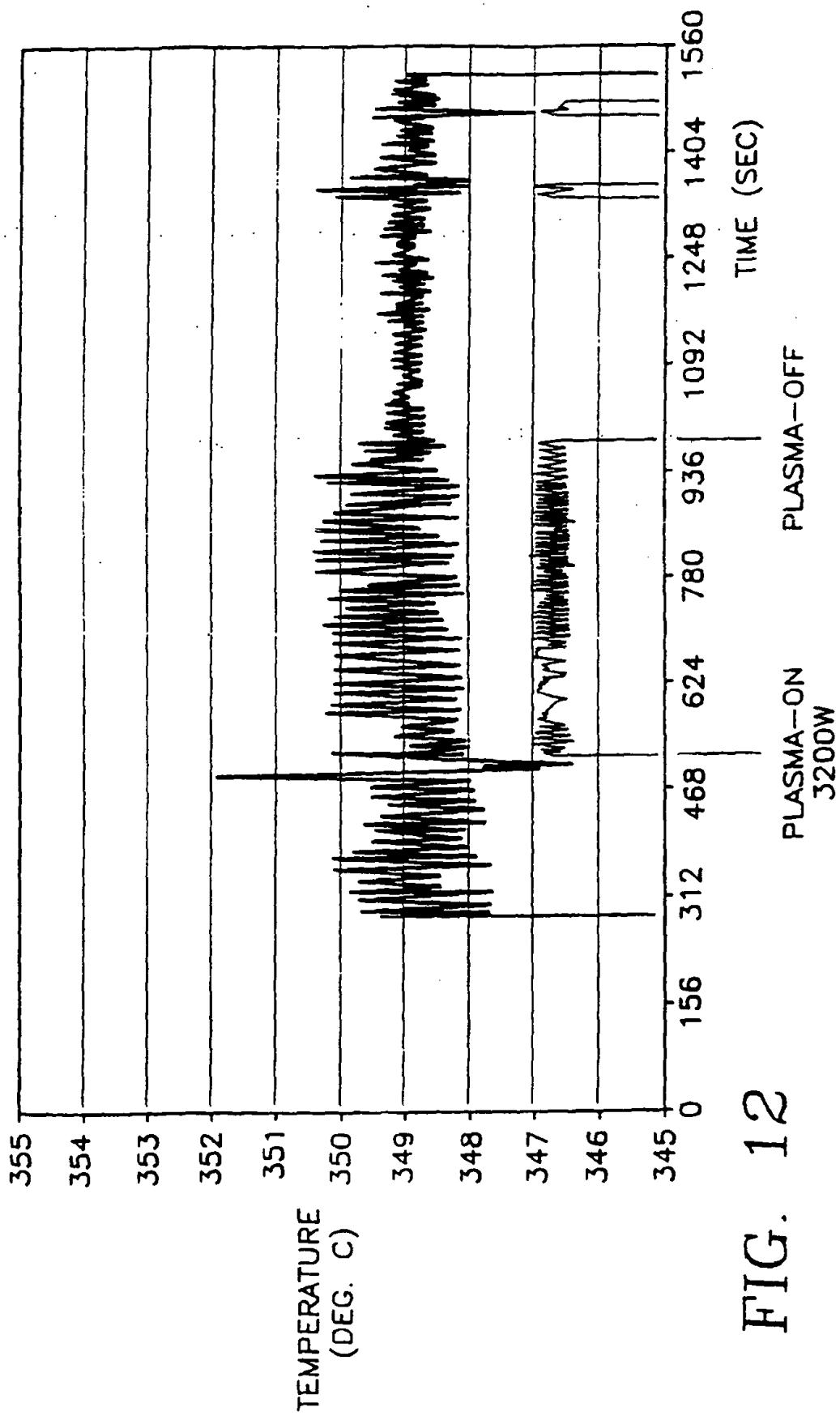


FIG. 12



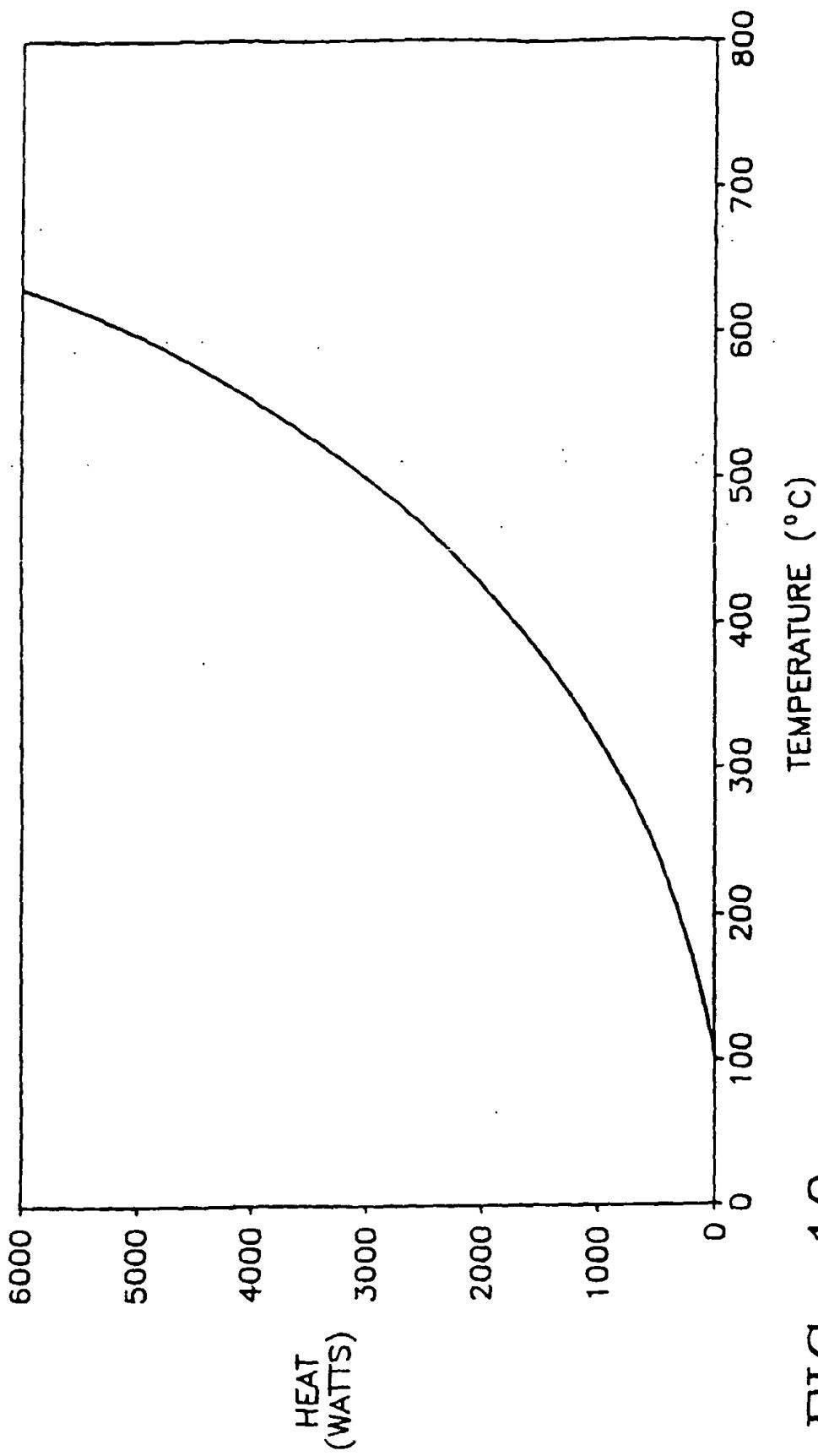
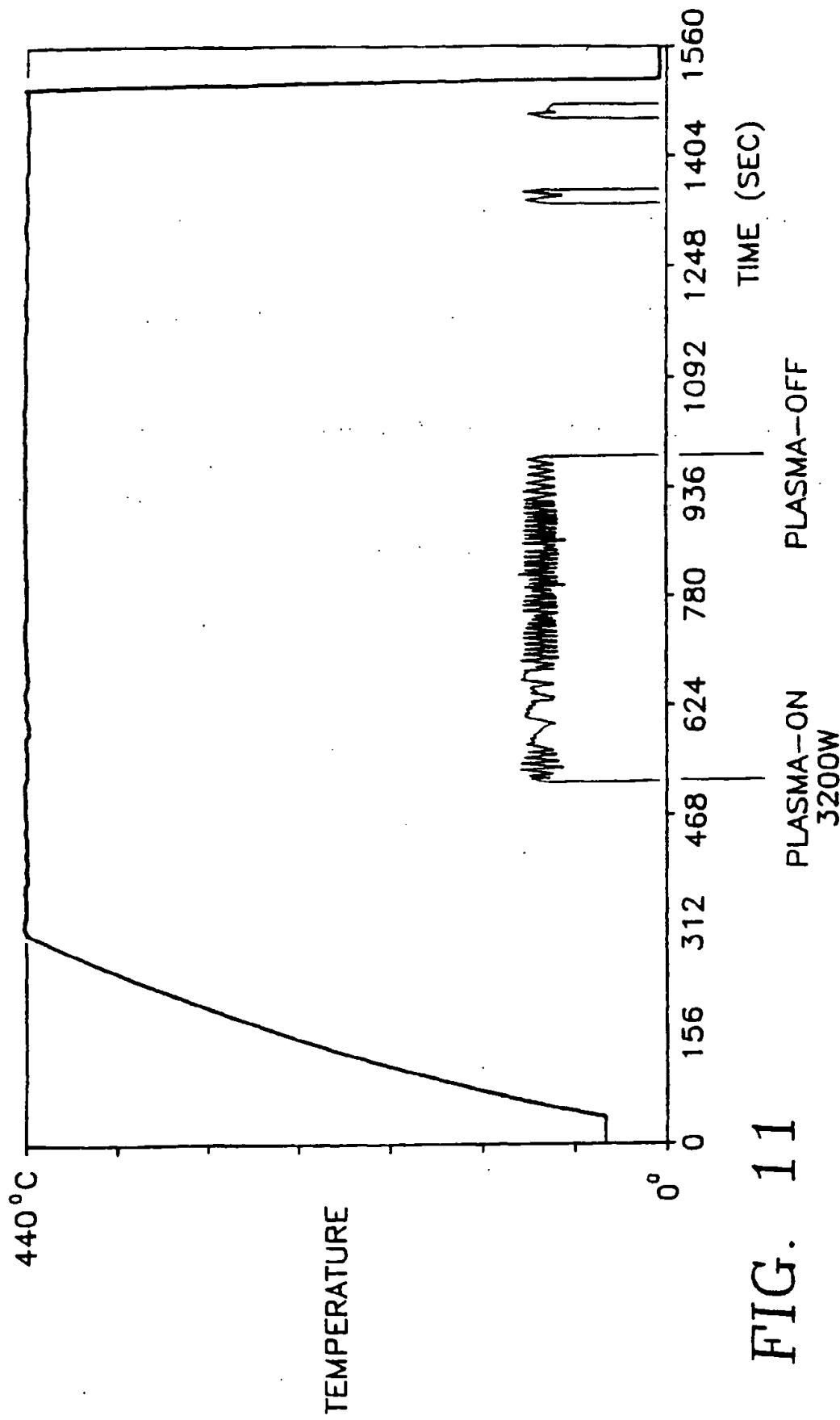


FIG. 10



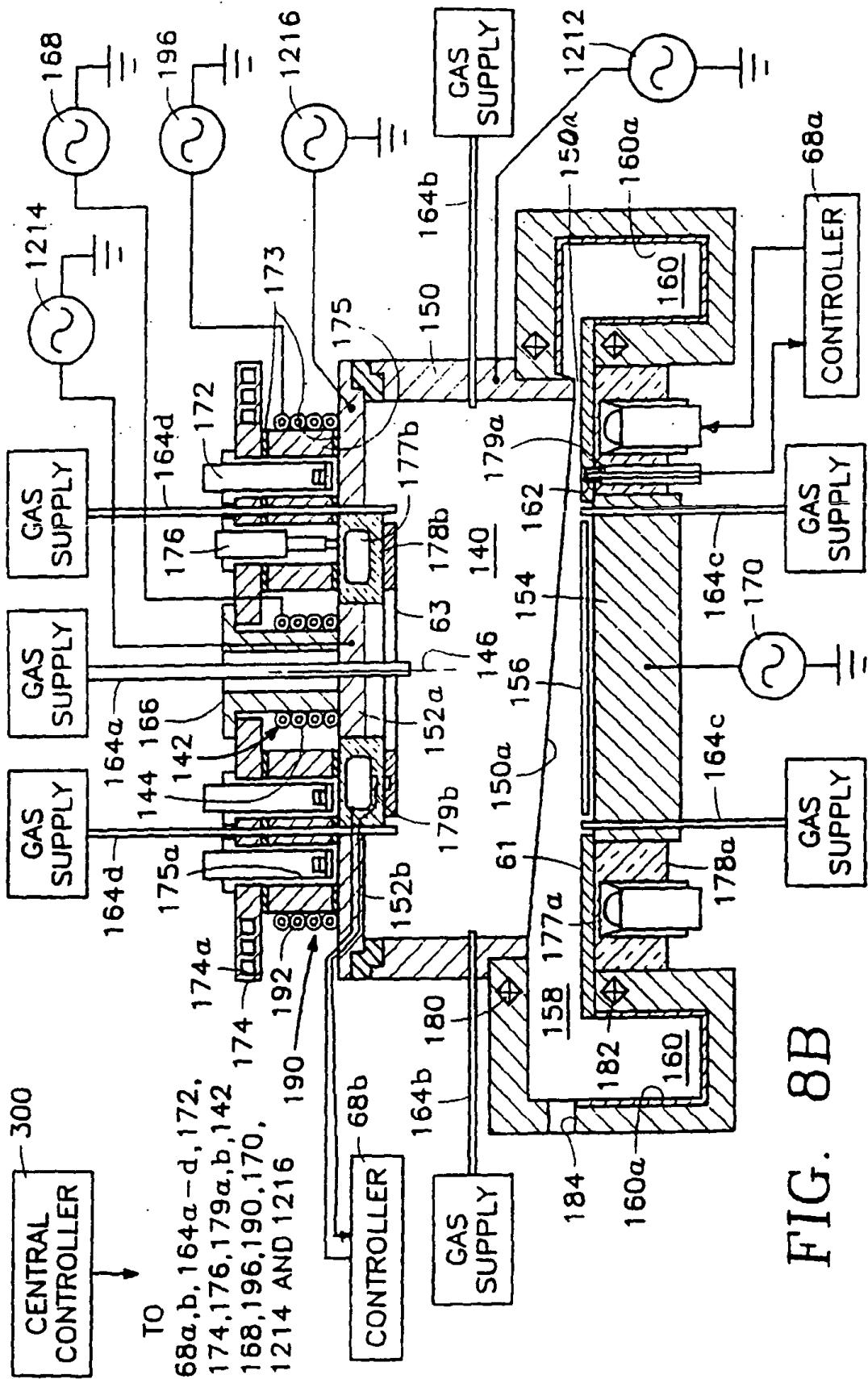


FIG. 8B

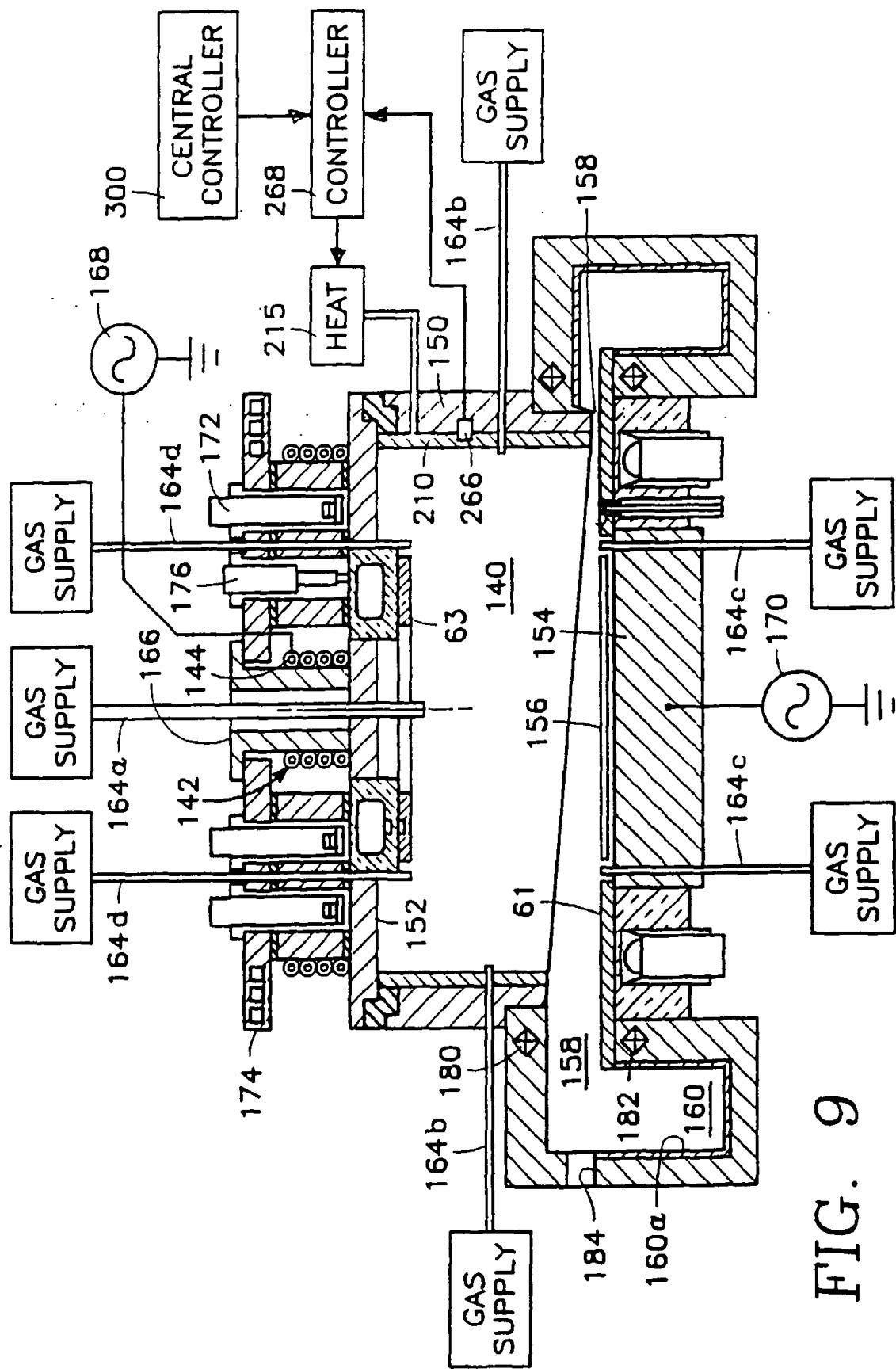


FIG. 9

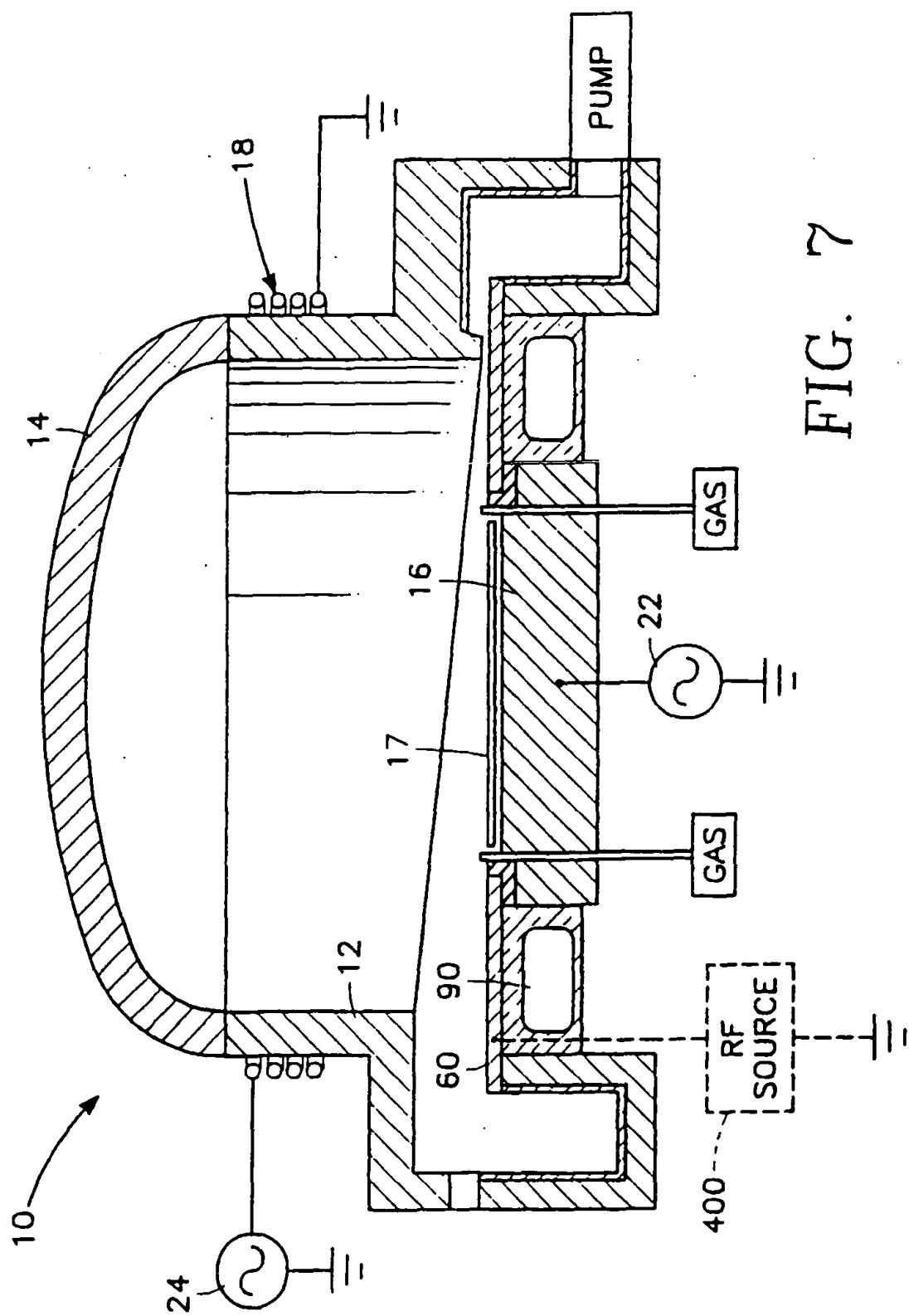


FIG. 7

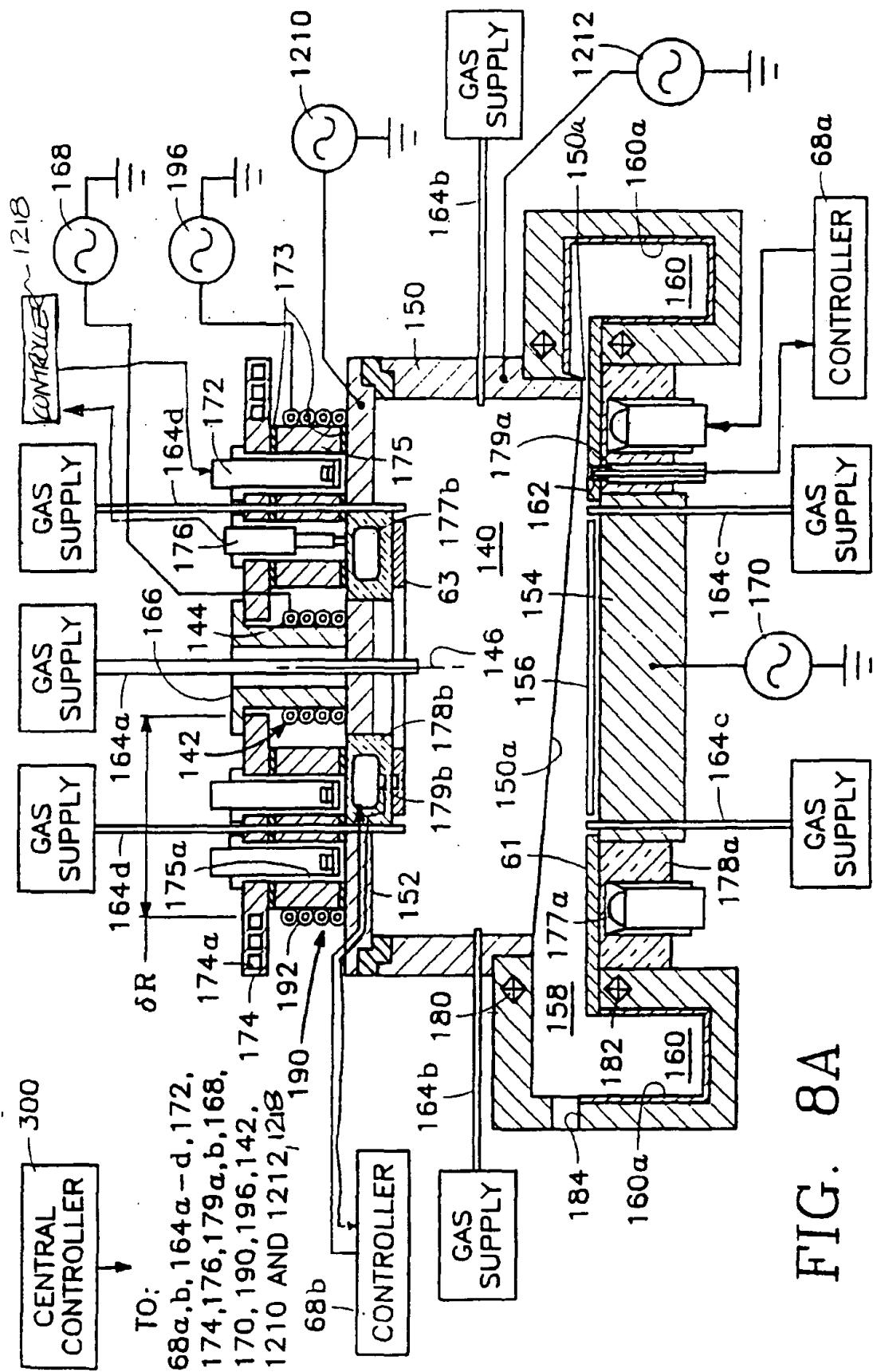


FIG. 8A

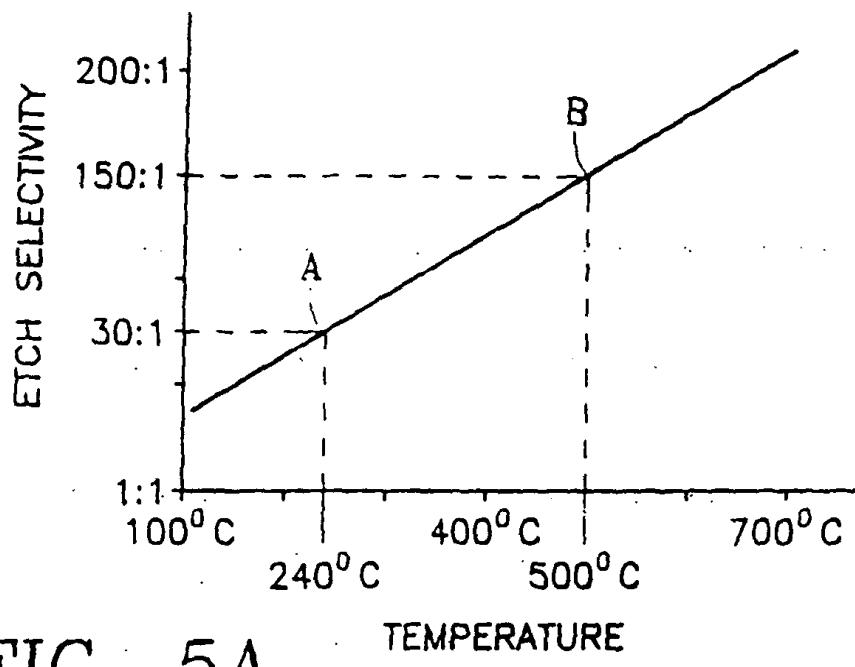


FIG. 5A

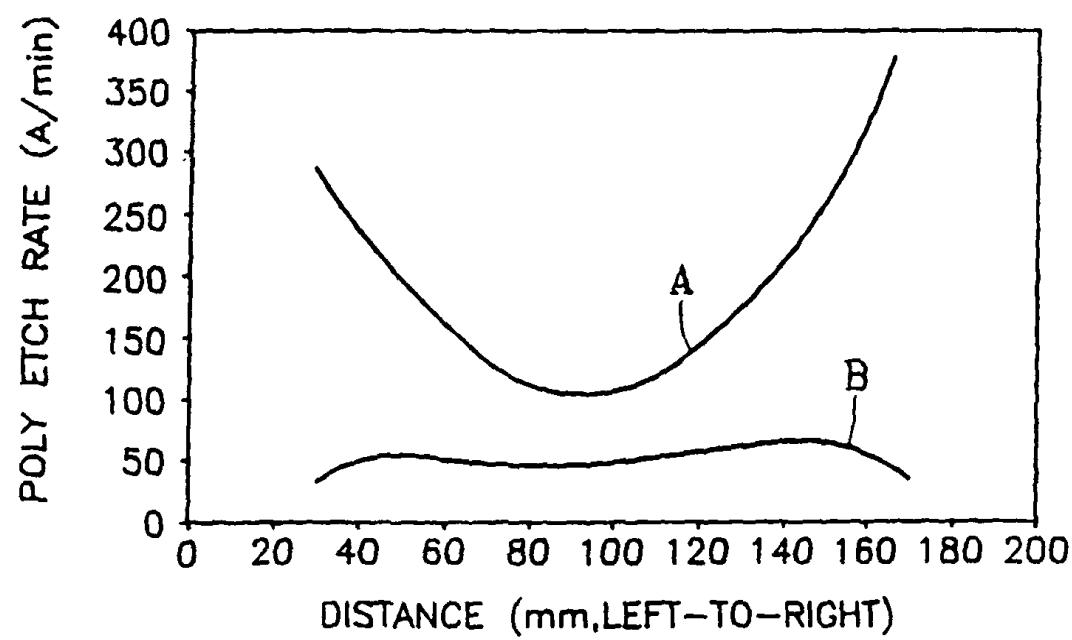


FIG. 5B

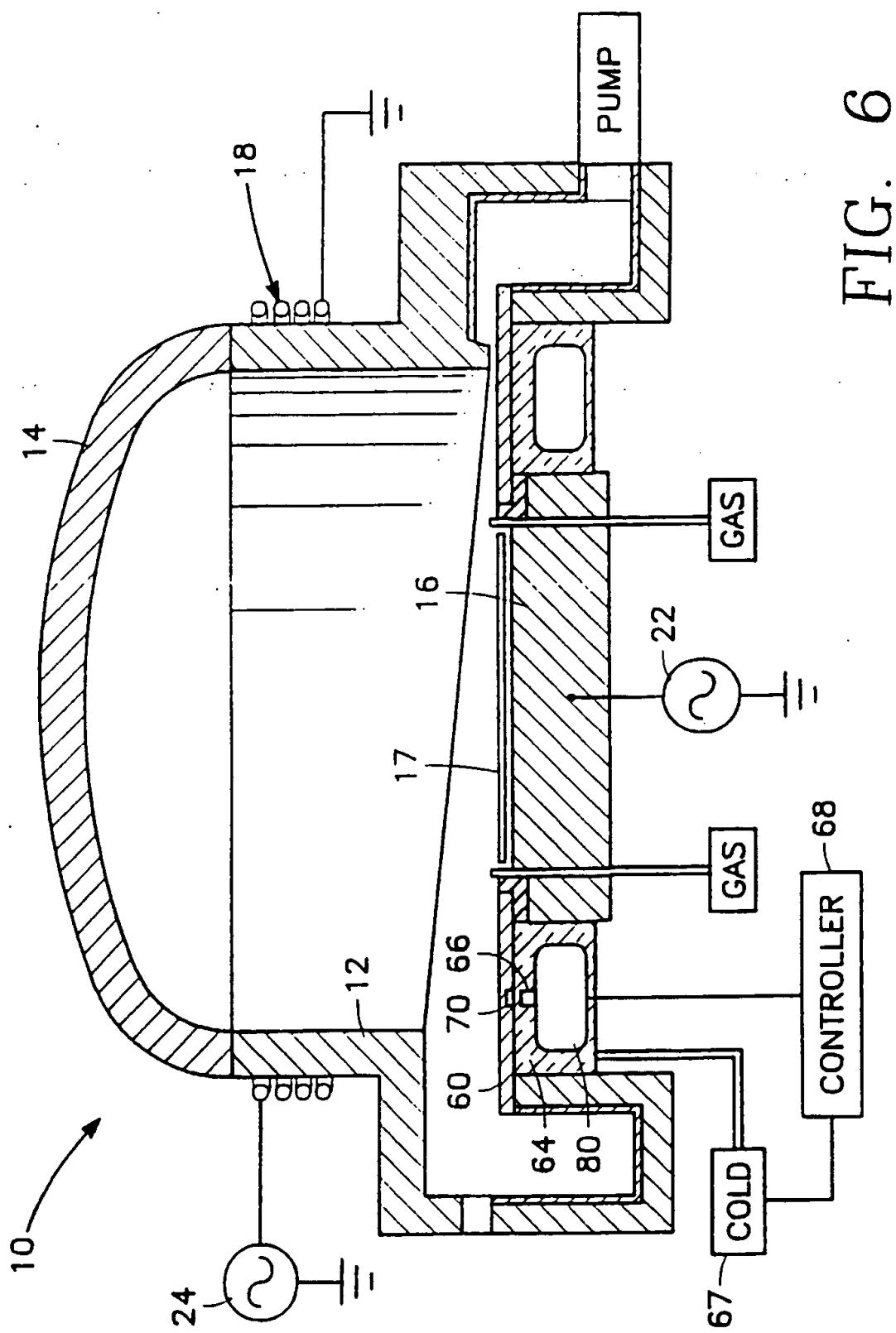


FIG. 6

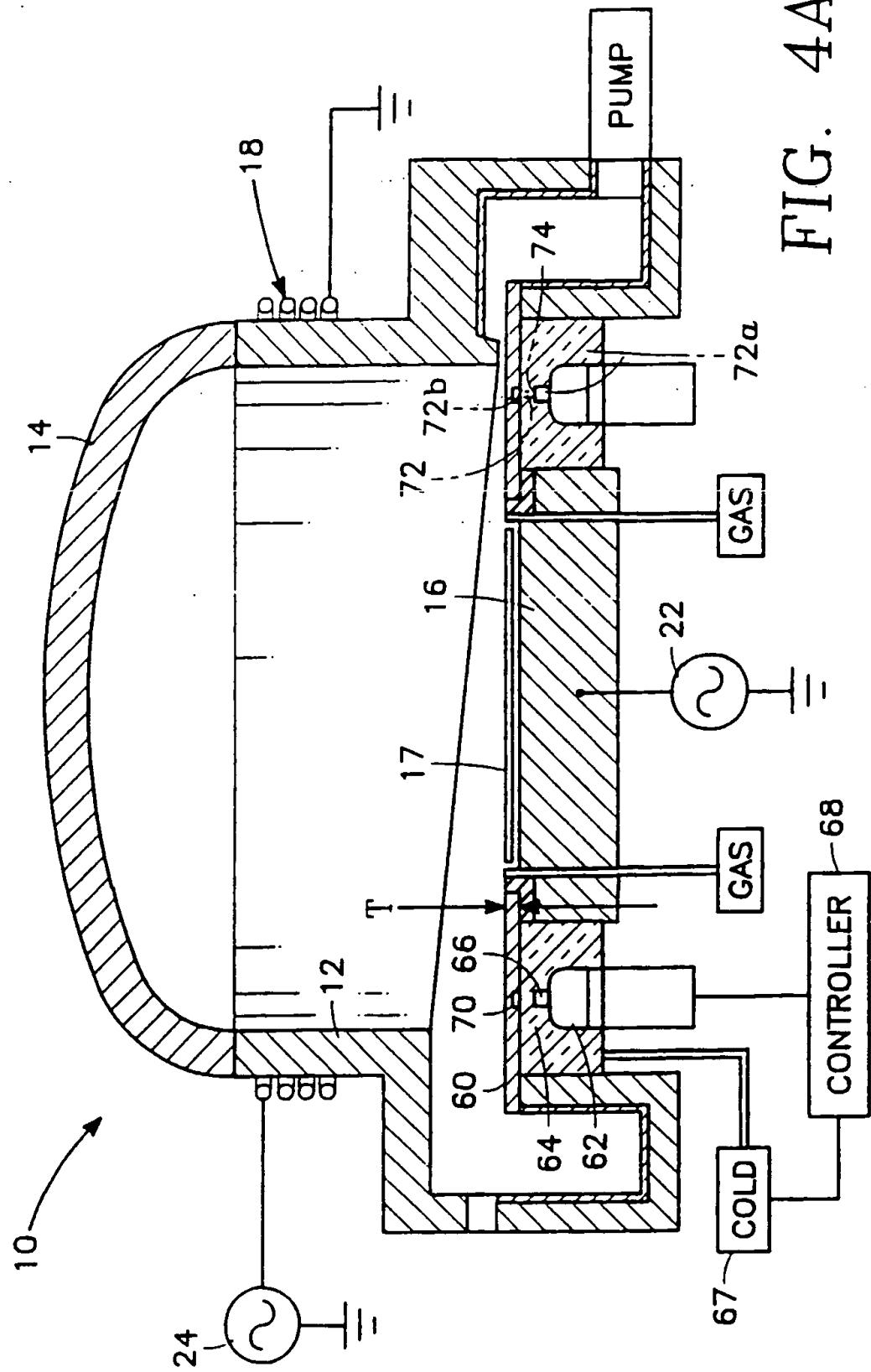
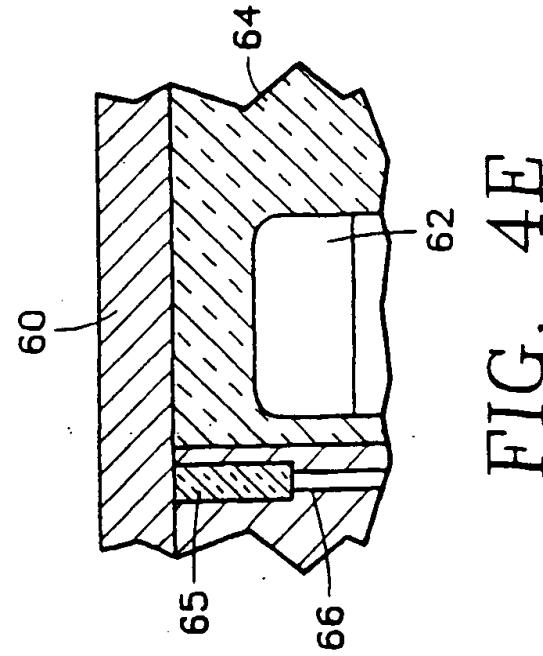
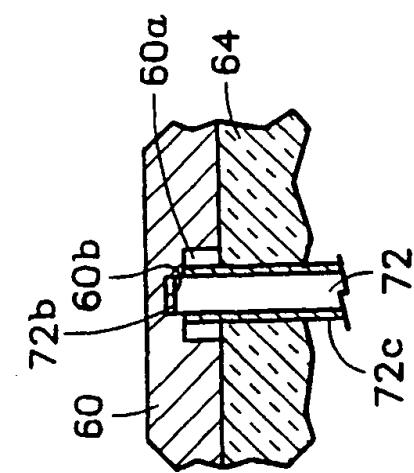
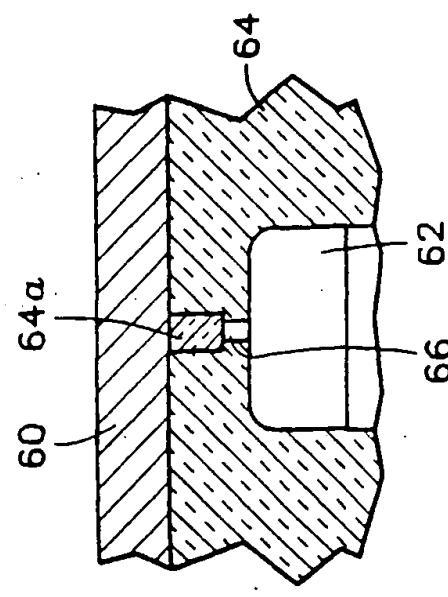
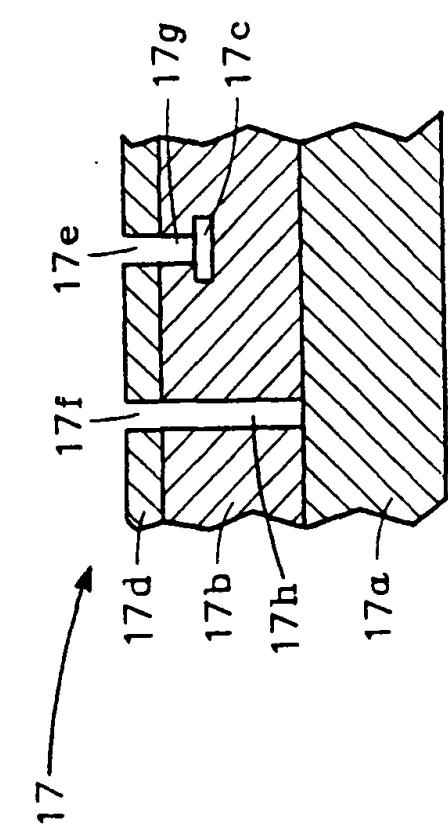


FIG. 4A



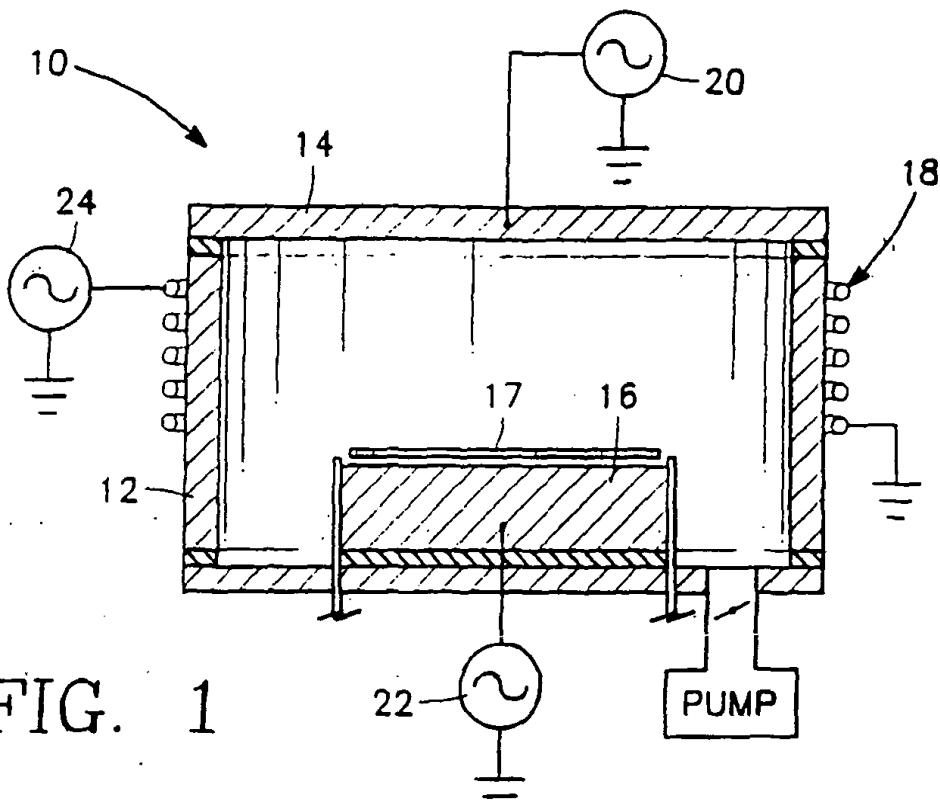


FIG. 1

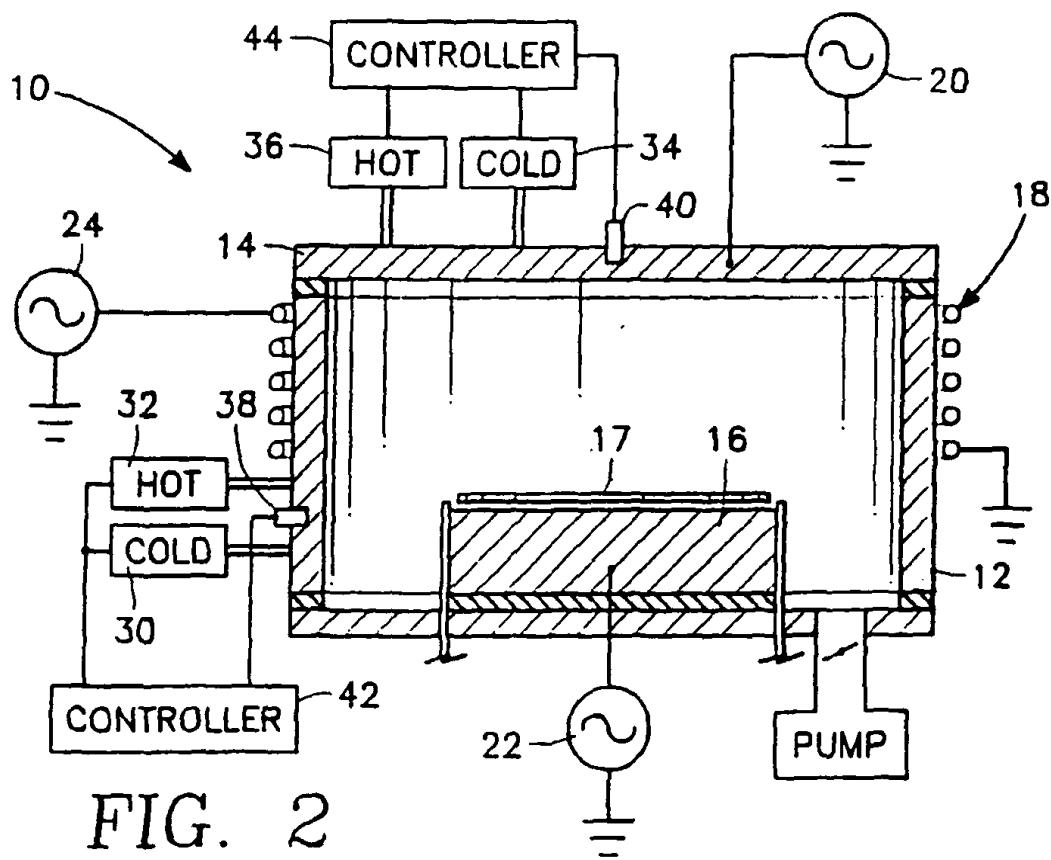


FIG. 2

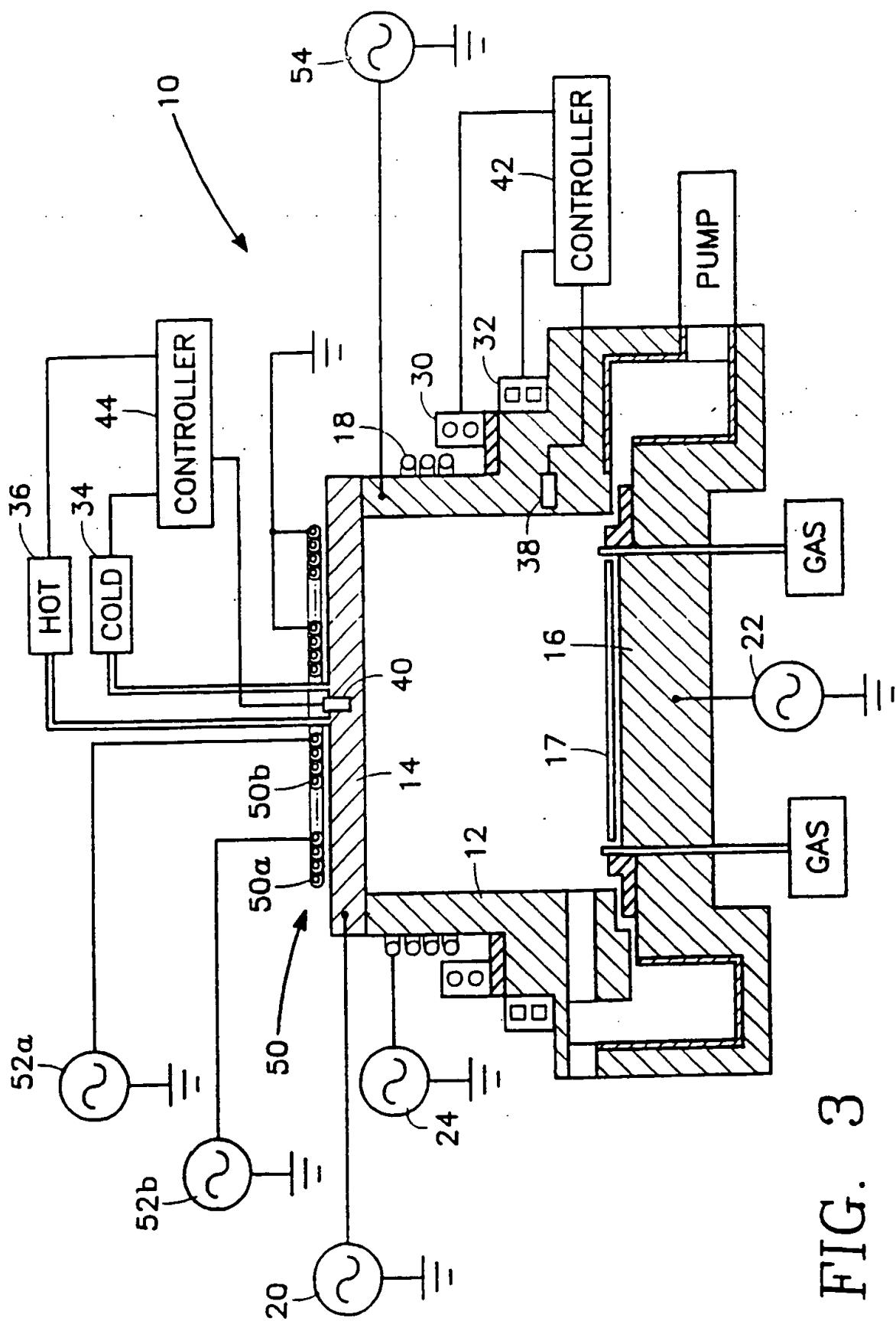


FIG. 3

further comprising an optical conduit between said sensor and a selected portion of said polymer-hardening precursor piece, said conduit being transmissive at said sensor wavelength.

51. A reactor as claimed in claim 50 further comprising a temperature sensitive material planted on said selected portion of said polymer-hardening precursor piece and wherein said sensor wavelength coincides with an emission wavelength of said temperature sensitive material.

52. A reactor as claimed in claim 51 wherein said temperature sensitive material comprises a fluoro-optical material and wherein said sensor comprises a fluoro-optical probe.

53. A reactor as claimed in claim 51 wherein said temperature sensitive material comprises a substance whose emissivity is at least nearly invariant with its temperature and said sensor comprises an optical pyrometer.

54. A reactor as claimed in claim 53 wherein said temperature sensitive material comprises silicon nitride.

55. A reactor as claimed in any one of claims 50 to 54 wherein said optical conduit comprises an optical fiber having one end facing said sensor and another end facing said selected portion of said polymer-hardening precursor piece.

56. A reactor as claimed in any one of claims 50 to 55 wherein said optical conduit comprises a port within said window.

57. A reactor as claimed in any one of claims 50 to 56 wherein said optical conduit comprises a second window.

58. A reactor as claimed in any one of claims 50 to 57 wherein said sensor wavelength coincides with an emission wavelength of said removable expendable piece, and wherein said optical conduit comprises a long wavelength transmissive material.

59. A reactor as claimed in any one of claims 50 to 58 wherein said sensor wavelength lies in a range of wavelengths longer than that of visible light.

60. A reactor as claimed in claim 58 or claim 59 wherein said transmissive material is a member of a class of materials comprising zinc selenide and sapphire.

61. A reactor as claimed in any one of claims 50 to 60 wherein the material of said optical conduit does not radiate strongly at said sensor wavelength in re-

sponse to being heated

62. A reactor as claimed in claim 49 wherein said window absorbs radiation emitted by said polymer-hardening precursor piece for radiant cooling of said polymer-hardening precursor piece.

63. A reactor as claimed in claim 62 further comprising a cooler coupled to said window.

64. A reactor as claimed in claim 55 further comprising a bore hole in said selected portion of said polymer-hardening precursor piece, said one end of said optical fiber facing bore hole.

65. A reactor as claimed in claim 64 wherein:

20 emissivity of said polymer-hardening precursor piece varies with temperature;

25 said one end of said optical fiber extends inwardly at least partially into said bore hole; and said bore hole has a sufficiently high aspect ratio to reduce apparent variation of said emissivity with temperature observed by said sensor.

66. A reactor as claimed in claim 64 or claim 65 wherein said optical fiber is countersunk into a top portion of said bore hole.

30 67. A reactor as claimed in claim 66 further comprising an opaque shield surrounding a portion of said optical fiber extending out of said hole.

68. A plasma etching process comprising:

35 providing a chamber within which to carry out said process;

40 supporting an article to be processed on a support in the chamber;

45 supplying a process gas containing at least etchant and polymer precursor materials;

generating a plasma within said chamber;

providing, in addition to said process gas, a source material of silicon or carbon in said chamber;

applying RF bias power to said source material to at least maintain a surface of said source reactive with said plasma.

50 69. A plasma etching process comprising:

55 providing a chamber within which to carry out said process;

supporting an article to be processed on a support in the chamber;

suppling a process gas containing at least etchant and polymer precursor materials;

generating a plasma within said chamber;

providing, in addition to said process gas, a source material of a polymer-hardening precursor in said chamber;  
applying RF bias power to said source material to at least maintain a surface of said source reactive with said plasma. 5

70. A process as claimed in claim 68 or claim 69 wherein in said etch process etches first and second different materials on said article at first and second etch rates respectively, said first etch rate being greater than said second etch rate corresponding to an etch selectively of said first material to said second material which is a function of said first and second etch rates. 10 15

71. A process as claimed in any one of claims 3 to 10, 13 to 32 and 70 wherein said first material overlies said second material and said etchant creates openings through said first material to expose portions of said second material. 20

72. A process as claimed in claim 71 wherein:

    said polymer precursor material provides material for polymer deposition on the exposed portions of said second material;  
    said etchant precursor material provides material for etching said article; and  
    said polymer deposition reduces etching of said second material to enhance etch selectivity. 25 30

73. A process as claimed in claim 72 wherein:

    a photoresist mask layer over said first material has openings therethrough defining said openings; and  
    said polymer deposition reduces etching of said second material and of said photoresist material to enhance etch selectivity. 35 40

74. A process as claimed in any one of claims 3 to 10, 13 to 32 and 70 to 73 wherein said first material comprises an oxygen-containing material and said second material comprises a non-oxygen containing material. 45

15. A process as claimed in claim 14 wherein said temperature range is such that polymer formed on said wafer comprises material from said polymer-hardening precursor material.

16. A process as claimed in any one of claims 13 to 15 wherein said first material comprises an oxide, said second material comprises silicon or polysilicon, said etchant precursor of said process gas comprises fluorine, said polymer precursor of said process gas comprises at least fluorine and carbon and said polymer-hardening precursor material comprises silicon.

17. A process as claimed in any one of claims 3 to 10 and 13 to 16 wherein said temperature range lies above about 100°C, preferably above about 220°C.

18. A process as claimed in any one of claims 3 to 10 and 13 to 16 wherein said temperature range lies between 180°C and 220°C.

19. A process as claimed in any one of claims 3 to 10 and 13 to 16 wherein said temperature range lies between about 300°C and 700°C.

20. A process as claimed in any one of claims 3 to 10 and 13 to 16 wherein said temperature range lies between about 240°C and 500°C.

21. A process as claimed in any one of claims 11 to 16 further comprising applying RF power to said polymer-hardening precursor material.

22. A process as claimed in claim 21 wherein said RF power applied to said polymer-hardening precursor material and said heating of said polymer-hardening precursor material together are sufficient to maintain a surface thereof reactive with said plasma.

23. A process as claimed in claim 21 or claim 22 wherein said polymer-hardening precursor material comprises a scavenger for an etchant derived from said etchant precursor, and wherein said RF power applied to said polymer-hardening precursor material is sufficient to promote a significant scavenging of said etchant.

24. A process as claimed in claim 21 or claim 22 wherein said RF power is applied to said polymer-hardening precursor material at an RF power level substantially reduced from a reference power level at which said polymer-hardening precursor material provides a significant amount of fluorine scavenger material into said plasma near said polymer condensation temperature, while increasing said target temperature to compensate for the reduction in RF power.

25. A process as claimed in claim 10 or claim 24 wherein said RF power level is reduced by at least an integer number below said reference power level while said target temperature is only fractionally increased.

26. A process as claimed in claim 25 wherein said RF power level is reduced approximately four-fold below said reference power level and said target temperature is increased to about 240°C.

27. A process as claimed in any one of claims 11 to 26 wherein said polymer-hardening precursor material is a member of a class of materials comprising silicon, carbon, silicon carbide and silicon nitride.

28. A process as claimed in any one of claims 11 to 27 wherein the step of providing said polymer-hardening precursor material comprises providing a quickly removable piece of said polymer-hardening precursor material separate from integral structures of said reactor chamber.

29. A process as claimed in any one of claims 11 to 28 wherein the step of heating comprises one of: (a) inductively heating and (b) radiantly heating.

30. A process as claimed in claim 29 wherein the step of heating further comprises controlling a temperature of said polymer-hardening precursor material to a selected temperature by measuring said temperature by sensing radiation from said polymer-hardening precursor material and heating said precursor material so as to maintain the measured temperature near said selected temperature.

31. A process as claimed in claim 30 wherein the step of measuring comprises remotely sensing radiation from said polymer-hardening precursor material through a port, and the step of heating comprises heating said polymer-hardening precursor material through a window, wherein said port is one of: (a) a portion of said window, (b) separate from said window.

32. A process as claimed in claim 31 wherein the step of heating comprises radiating heat at a wavelength for which said window is at least nearly transmissive and wherein the step of measuring temperature comprises sensing radiation from said polymer-hardening precursor material at a wavelength at which said port is at least nearly transmissive.

33. A plasma reactor comprising:

a reactor chamber;

plasma source power coupling apparatus near said chamber and an RF power source for supply RF power to said plasma source power coupling apparatus;

a process gas inlet and a process gas supply coupled to said inlet for furnishing a process gas containing etchant and polymer precursors;

a support for holding an article to be processed inside said reactor chamber;

a polymer-hardening precursor piece inside said chamber.

34. A reactor as claimed in claim 33 further comprising:  
a heater for heating said polymer-hardening precursor piece sufficiently to permit said polymer-hardening precursor piece to react with a plasma in said reactor chamber.

35. A reactor as claimed in claim 33 or claim 34 wherein said polymer-hardening precursor piece comprises an expendable removable piece separable from structural elements of said chamber.

36. A reactor as claimed in any one of claims 33 to 35 wherein emissivity of said polymer-hardening precursor piece varies with temperature, said reactor further comprising:  
a bore hole in said polymer-hardening precursor piece;  
a temperature sensor and an optical fiber coupling said temperature sensor to said bore hole, said one end of said optical fiber extending inwardly at least partially into said bore hole; and wherein said bore hole has a sufficiently high aspect ratio to reduce apparent variation of said emissivity with temperature observed by said sensor.

37. A reactor as claimed in any one of claims 33 to 36 further comprising an RF power source coupled to said polymer-hardening precursor piece.

38. A reactor as claimed in any one of claims 33 to 37 wherein said polymer-hardening precursor material affects polymerization on a surface of said article by increasing a resistance to etching of a polymer formed on said surface in accordance with a temperature at which said polymer-hardening precursor piece is held.

39. A reactor as claimed in claim 38 wherein said polymer-hardening precursor piece is of a material which contributes material into said polymer when held at a sufficiently high temperature, said material contributed to said polymer by said polymer-hardening precursor increasing an extent to which said polymer is resistant to etching by an etchant derived from an etchant precursor of said process gas

40. A reactor as claimed in any one of claims 33 to 39 wherein said polymer-hardening material is a scavenger for an etchant derived from an etch precursor of said process gas.

41. A reactor as claimed in any one of claims 33 to 40 wherein said process gas comprises at least fluorine and carbon and said polymer-hardening precursor piece comprises one of: (a) silicon, (b) carbon, (c) silicon carbide, (d) silicon nitride.

42. A reactor as claimed in any one of claims 33 to 41 wherein said article being processed comprises a planar wafer and said polymer-hardening precursor piece comprises an annular planar ring concentric with and near a circumference of said wafer.

43. A reactor as claimed in claim 42 wherein said ring is at least nearly co-planar with said wafer.

44. A reactor as claimed in any one of claims 34 to 43 wherein said heater is remote from said polymer-hardening precursor piece and comprises one of:  
(a) an inductive heater and (b) a radiant heater.

45. A reactor as claimed in any one of claims 34 to 43 further comprising a remote temperature sensor responsive at a sensor wavelength for measuring a temperature of said polymer-hardening precursor piece and a controller connected to receive a signal from said remote temperature sensor and connected to a control input of said heater to govern said heater in response to said remote temperature sensor.

46. A reactor as claimed in claim 44 or claim 45 wherein said heater is a radiant heater emitting heat at a heater wavelength within an absorption spectrum of said polymer-hardening precursor piece.

47. A reactor as claimed in claim 46 wherein said heater wavelength and said sensor wavelength are different.

48. A reactor as claimed in claim 46 wherein said heater wavelength and said sensor wavelength lie within at least partially coinciding wavelength ranges.

49. A reactor as claimed in any one of claims 46 to 48 further comprising a window separating said heater and sensor from said polymer-hardening precursor piece, said window being transmissive at least at said heater wavelength.

50. A reactor as claimed in any one of claims 45 to 48

support pedestal top surface plane. It may be of any shape and at any location, provided that it is not too distant from the heat source to be efficiently heated thereby and provided that it shields the plasma processing region of the chamber from the heat source (so as to avoid diversion of power from the heat source to plasma generation in the chamber). In the preferred embodiment some shielding of the plasma from energy of the heat source (in addition to that provided by the silicon ring 60 itself) is provided by a pair of ring magnets 100, 102 that prevent plasma flow between the plasma processing region of the chamber and the pumping annulus.

Another embodiment that provides the requisite shielding and close proximity of the expendable polymer-hardening precursor piece to a remote heat source is illustrated in FIG. 9 in which the expendable piece is a cylindrical silicon liner 210 abutting the cylindrical chamber side wall interior surface. A peripheral heat source 215 adjacent the outside of the cylindrical side wall heats the silicon liner 210 through the side wall. The peripheral heat source 215 may be an induction heater, in which case the cylindrical chamber wall is either an insulator such as quartz or is a semiconductor such as silicon of sufficiently high resistivity to minimize absorption and maximize transmission of the induction field of the heat source 215 to the liner 210. Alternatively, the peripheral heat source 215 is a radiant heater such as a tungsten halogen lamp or an electric discharge lamp. A temperature sensor 266 and temperature controller 268 governing operation of the peripheral heater 215 perform temperature control. In the embodiment of FIG. 9, the master controller 300 governs the temperature controller 168.

The graph of FIG. 10 illustrates the performance of a temperature control system implemented in the embodiment of FIG. 6. The horizontal axis is the steady state temperature in degrees Celsius at which the temperature controller 68 has been commanded to hold the silicon ring 60, while the vertical axis is the applied power in Watts required to maintain the selected ring temperature. The graph of FIG. 11 illustrates the closed loop temperature response of the system of FIG. 6, the horizontal axis being time in seconds and the vertical axis being the ring temperature in degrees Celsius. In the graph of FIG. 11, the ring 60 begins at an initial temperature near room temperature and, after about 30 seconds, the controller 68 is commanded to put the ring temperature at 440°C. This temperature is reached at about 310 seconds with no overshoot and only a trace amount of system noise. At about 550 seconds a plasma is ignited in the chamber and is extinguished at about 1000 seconds, the effect on the ring temperature being almost unobservable in FIG. 11. This latter event proves the stability of the temperature control system and its responsiveness. FIG. 12 is a greatly enlarged view of a portion of the graph of FIG. 11 in the neighborhood of the time window from 301 seconds (when the target

temperature is reached with no overshoot) and including 550 seconds (when the plasma is temporarily turned on). The plasma was ignited with 3.2 kWatts of source power at 550 seconds and the enlarged view of FIG. 12 reveals a short spike in the ring temperature coincident with that event. This data was obtained using the fluor-optical probe version of the sensor 66 and the optical fiber 72.

In lieu of heating the polymer hardening precursor

piece (e.g., the silicon ring 60), RF bias power may be applied from a source 400 (indicated in dashed line in FIG. 7) to the silicon ring 60 to achieve a desired effect in increasing polymer resistance to etching. The skilled worker can readily ascertain the requisite RF bias power level for this application by increasing the RF bias power on the piece (e.g., the silicon ring 60) to a threshold level at which polymer deposition no longer accumulates on the piece so that the surface of the piece remains free for interaction with the plasma. Furthermore, increasing the RF bias power applied to the piece (e.g., the silicon ring 60) beyond this threshold level actually increases the polymer hardness on the wafer and consequently increases the etch selectivity beyond that achieved at the threshold RF bias power level. While this may be practiced as an alternative mode of the invention, it is not the most preferable mode because: (a) the consumption of the polymer hardening precursor piece will be higher, and (b) some electrical (RF) coupling to the polymer hardening precursor piece must be provided to impose the requisite RF bias power on it, complicating its structure. In yet another alternative mode, heating and RF biasing of the polymer hardening precursor piece may be combined.

While the invention has been described as being

carried out with a number of separate RF sources, some or all of the RF sources depicted herein may derive their outputs from separate RF generators or from a common RF generator with different outputs at different RF power levels, frequencies and phases synthesized with variable power dividers, frequency multipliers and/or phase delays, as may be appropriate. Moreover, while the invention has been described as being carried out with a number of separate process gas supplies, some or all of the process gas supplies may be derived from a common process gas supply which is divided among the plural separately controlled gas inlets 64.

While the invention has been described in detail by

specific reference to preferred embodiments thereof, it is understood that variations and modifications thereof may be made without departing from the true spirit and scope of the invention.

#### Claims

55 1. A plasma etch process comprising:

providing a chamber within which to carry out

said process.

supporting an article to be processed on a support in the chamber;

supplying a process gas containing at least etchant and polymer precursor materials;

providing, in addition to said process gas, a source material of silicon or carbon in said chamber;

generating a plasma within said chamber;

heating said source material sufficiently to at least maintain a surface of said source reactive with said plasma.

2. A process as claimed in claim 1 wherein the step of heating comprises heating said source material to at least a polymer condensation temperature.

3. A process as claimed in claim 2 wherein said etch process etches first and second different materials on said article at first and second etch rates respectively, said first etch rate being greater than said second etch rate corresponding to an etch selectivity of said first material to said second material which is a function of said first and second etch rates, and wherein said heating step further comprises:

increasing a temperature of said source material into a temperature range above said polymer condensation temperature to increase said etch selectivity.

4. A process as claimed in claim 2 or claim 3 wherein said heating step further comprises:

increasing a temperature of said source material into a temperature range above said polymer condensation temperature.

5. A process as claimed in claim 4 wherein said temperature range is one wherein polymer formed on said wafer contains an amount of said source material.

6. A process as claimed in any one of claims 3 to 5 wherein said first material comprises an oxide, said second material comprises silicon or polysilicon, an etchant precursor of said process gas comprises fluorine, a polymer precursor of said process gas comprises at least fluorine and carbon and said source material comprises silicon.

7. A process as claimed in any one of claims 1 to 6 further comprising applying RF power to said source material.

8. A process as claimed in claim 7 wherein said RF power applied to said source material and said heating of said source material together are sufficient to maintain said surface thereof reactive with

said plasma.

9. A process as claimed in claim 7 or claim 8 wherein said source material comprises a scavenger for an etchant derived from said etchant precursor, and wherein said RF power applied to said source material is sufficient to promote significant scavenging of said etchant.

10. A process as claimed in claim 6 further comprising applying RF power to said source material at an RF power level substantially reduced from a reference power level at which said source material when near said polymer condensation temperature provides a significant amount of fluorine scavenger material into said plasma, while increasing the temperature of said source material to compensate for the reduction in RF power.

11. A plasma etch process comprising:

providing a chamber within which to carry out said process;

supporting an article to be processed on a support in the chamber;

supplying a process gas containing at least etchant and polymer precursor materials;

providing a polymer-hardening precursor material in said chamber;

generating a plasma within said chamber;

heating said precursor material sufficiently to at least maintain a surface of said precursor material reactive.

12. A process as claimed in claim 11 wherein the step of heating comprises heating said precursor material to at least a polymer condensation temperature.

13. A process as claimed in claim 12 wherein said etch process etches first and second different materials on said article at first and second etch rates respectively, said first etch rate being greater than said second etch rate corresponding to an etch selectivity of said first material to said second material which is a function of said first and second etch rates, and wherein said heating step further comprises:

increasing a temperature of said polymer-hardening precursor material to a temperature range above said polymer condensation temperature to achieve a corresponding increase in said etch selectivity.

14. A process as claimed in claim 12 wherein said heating step heats said polymer-hardening precursor material to a temperature range above said polymer condensation temperature.

ymmer condensation temperature, for example, as disclosed in the referenced co-pending application.

A wafer slit valve 184 through the exterior wall of the pumping annulus 160 accommodates wafer ingress and egress. The annular opening 158 between the chamber 140 and pumping annulus 160 is larger adjacent the wafer slit valve 184 and smallest on the opposite side by virtue of a slant of the bottom edge 150a of the cylindrical side wall 150 so as to make the chamber pressure distribution more symmetrical with a non-symmetrical pump port location.

A second outer vertical stack or solenoid 1120 of windings 1122 at an outer location (i.e. against the outer circumferential surface of the thermally conductive torus 175) is displaced by a radial distance  $\delta R$  from the inner vertical stack of solenoidal windings 144. Note that confinement of the inner solenoidal antenna 142 to the center and the outer solenoidal antenna 1120 to the periphery leaves a large portion of the top surface of the ceiling 152 available for direct contact with the temperature control apparatus 172, 174, 175. An advantage is that the larger surface area contact between the ceiling 152 and the temperature control apparatus provides a more efficient and more uniform temperature control of the ceiling 152.

For a reactor in which the side wall and ceiling are formed of a single piece of silicon for example with an inside diameter of 12.6 in (32 cm), the wafer-to-ceiling gap is 3 in (7.5 cm), and the mean diameter of the inner solenoid was 3.75 in (9.3 cm) while the mean diameter of the outer solenoid was 11.75 in (29.3 cm) using 3/16 in diameter hollow copper tubing covered with a 0.03 thick teflon insulation layer, each solenoid consisting of four turns and being 1 in (2.54 cm) high. The outer stack or solenoid 1120 is energized by a second independently controllable plasma source RF power supply 196. The purpose is to permit different user-selectable plasma source power levels to be applied at different radial locations relative to the workpiece or wafer 156 to permit compensation for known processing non-uniformities across the wafer surface, a significant advantage. In combination with the independently controllable center gas feed 164a and peripheral gas feeds 164b-d, etch performance at the workpiece center may be adjusted relative to etch performance at the edge by adjusting the RF power applied to the inner solenoid 142 relative to that applied to the outer solenoid 1120 and adjusting the gas flow rate through the center gas feed 164a relative to the flow rate through the outer gas feeds 164b-d. While the present invention solves or at least ameliorates the problem of a center null or dip in the inductance field as described above, there may be other plasma processing non-uniformity problems, and these can be compensated in the versatile embodiment of FIG. 8A by adjusting the relative RF power levels applied to the inner and outer antennas. For effecting this purpose with greater convenience, the respective RF power supplies 168, 196 for the inner and outer solenoids 142, 1120

may be replaced by a common power supply and a power splitter which can be variable to permit the user to change the relative apportionment of power between the inner and outer solenoids 142, 1120 while preserving a fixed phase relationship between the fields of the inner and outer solenoids 142, 1120. This is particularly important where the two solenoids 142, 1120 receive RF power at the same frequency. Otherwise, if the two independent power supplies 168, 196 are employed, then they may be powered at different RF frequencies, in which case it is preferable to install RF filters at the output of each RF power supply 168, 196 to avoid off-frequency feedback from coupling between the two solenoids. In this case, the frequency difference should be sufficient to time-average out coupling between the two solenoids and, furthermore, should exceed the rejection bandwidth of the RF filters. Another option is to make each frequency independently resonantly matched to the respective solenoid, and each frequency may be varied to follow changes in the plasma impedance (thereby maintaining resonance) in lieu of conventional impedance matching techniques. In such implementations, the frequency ranges of the two solenoids should be mutually exclusive. Preferably, however, the two solenoids are driven at the same RF frequency and in this case it is preferable that the phase relationship between the two be such as to cause constructive interaction or superposition of the fields of the two solenoids 142, 1120. Generally, this requirement will be met by a zero phase angle between the signals applied to the two solenoids if they are both wound in the same sense. Otherwise, if they are oppositely wound, the phase angle is preferably 180°. In any case, coupling between the inner and outer solenoids can be minimized or eliminated by having a relatively large space between the inner and outer solenoids 142, 1120.

The range attainable by such adjustments is increased by increasing the radius of the outer solenoid 1120 to increase the spacing between the inner and outer solenoids 142, 1120, so that the effects of the two solenoids 142, 1120 are more confined to the workpiece center and edge, respectively. This permits a greater range of control in superimposing the effects of the two solenoids 142, 1120. For example, the radius of the inner solenoid 142 should be no greater than about half the workpiece radius and preferably no more than about a third thereof. (The minimum radius of the inner solenoid 142 is affected in part by the diameter of the conductor forming the solenoid 142 and in part by the need to provide a finite non-zero circumference for an arcuate --e.g., circular-- current path to produce inductance.) The radius of the outer solenoid 1120 should be at least equal to the workpiece radius and preferably 1.5 or more times the workpiece radius. With such a configuration, the respective center and edge effects of the inner and outer solenoids 142, 1120 are so pronounced that by increasing power to the inner solenoid the chamber pressure can be raised into the hundreds of mT while

providing a uniform plasma, and by increasing power to the outer solenoid 1120 the chamber pressure can be reduced to on the order of 0.01 mT while providing a uniform plasma. Another advantage of such a large radius of the outer solenoid 1120 is that it minimizes coupling between the inner and outer solenoids 142, 1120.

In the embodiment of FIG. 8A, the ceiling 152 and side wall 150 are separate semiconductor (e.g., silicon) pieces insulated from one another having separately controlled RF bias power levels applied to them from respective RF sources to enhance control over the center etch rate and selectivity relative to the edge. As set forth in greater detail in above-referenced U.S. application Serial No. 08/597,577 filed February 2, 1996 by Kenneth S. Collins et al., the ceiling 152 may be a semiconductor (e.g., silicon) material doped so that it will act as an electrode capacitively coupling the RF bias power applied to it into the chamber and simultaneously as a window through which RF power applied to the solenoid 142 may be inductively coupled into the chamber. The advantage of such a window-electrode is that an RF potential may be established directly over the wafer (e.g., for controlling ion energy) while at the same time inductively coupling RF power directly over the wafer. This latter feature, in combination with the separately controlled inner and outer solenoids 142, 1120 and center and peripheral gas feeds 164a, 164b greatly enhances the ability to adjust various plasma process parameters such as ion density, ion energy, etch rate and etch selectivity at the workpiece center relative to the workpiece edge to achieve an optimum uniformity. In this combination, the respective gas flow rates through individual gas feeds are individually and separately controlled to achieve such optimum uniformity of plasma process parameters.

The lamp heaters 172 may be replaced by electric heating elements.

FIG. 8B illustrates another variation in which the ceiling 152 itself may be divided into an inner disk 152a and an outer annulus 152b electrically insulated from one another and separately biased by independent RF power sources 1214, 1216 which may be separate outputs of a single differentially controlled RF power source.

In accordance with an alternative embodiment, a user-accessible central controller 300 shown in FIGS. 8A and 8B, such as a programmable electronic controller including, for example, a conventional microprocessor and memory, is connected to simultaneously control gas flow rates through the central and peripheral gas feeds 164a, 164, RF plasma source power levels applied to the inner and outer antennas 142, 1120 and RF bias power levels applied to the ceiling 152 and side wall 150 respectively (in FIG. 8A) and the RF bias power levels applied to the inner and outer ceiling portions 152a, 152b (in FIG. 8B), temperature of the ceiling 152 and the temperature of the silicon rings 61, 63.

A ceiling temperature controller 1218 governs pow-

er applied to the ceiling heater lamps 172 by comparing the temperature measured by the ceiling temperature sensor 176 with a commanded target temperature for the ceiling 152 (received from the programmable controller 300). Similarly, the outer silicon ring temperature controller 68a governs power applied to the heater lamps 177a underlying the outer silicon ring 61 by comparing the temperature measured by the outer ring temperature sensor 179a with a commanded target temperature for the outer ring 61 (received from the programmable controller 300). Likewise, the inner silicon ring temperature controller 68b governs power applied to the heater lamps 177b overlying the inner silicon ring 63 by comparing the temperature measured by the inner ring temperature sensor 179b with a commanded target temperature for the inner silicon ring 63 (received from the programmable controller 300). The programmable controller 300 governs the target temperatures of the silicon ring temperature controllers 68a and 68b, the ceiling temperature controller 1218, the RF power levels of the solenoid power sources 168, 196, the RF power levels of the bias power sources 1210, 1212 (FIG. 8A) or 1214, 1216 (FIG. 8B), the wafer bias level applied by the RF power source 170 and the gas flow rates supplied by the various gas supplies (or separate valves) to the gas inlets 164a-d. The key to controlling the wafer bias level is the RF potential difference between the wafer pedestal 154 and the ceiling 152. Thus, either the pedestal RF power source 170 or the ceiling RF power source 1212 may be a short to RF ground. With the programmable controller 300, the user can easily optimize apportionment of RF source power, RF bias power, silicon emission and gas flow rate at the workpiece center relative to the workpiece periphery to achieve the greatest center-to-edge process uniformity across the surface of the workpiece (e.g., uniform radial distribution of etch rate and etch selectivity). Also, by adjusting (through the controller 300) the RF power applied to the solenoids 142, 1120 relative to the RF power difference between the pedestal 154 and ceiling 152, the user can operate the reactor in a predominantly inductively coupled mode or in a predominantly capacitively coupled mode.

While the various power sources connected in FIG. 8A to the solenoids 142, 1120, the ceiling 152, side wall 150 or the inner and outer ceiling portions 152a, 152b as in FIG. 8B) have been described as operating at RF frequencies, the invention is not restricted to any particular range of frequencies, and frequencies other than RF may be selected by the skilled worker in carrying out the invention.

In a preferred embodiment of the invention, the high thermal conductivity spacer 175, the ceiling 152 and the side wall 150 are integrally formed together from a single piece of crystalline silicon.

While the expendable polymer-hardening precursor piece has been described as a planar ring (60 in FIGS. 6 and 7 and 61 in FIGS. 8A and 8B) in the wafer

chamber 140. While in the illustrated embodiment the windings 144 are symmetrical and have an axis of symmetry coinciding with the center axis of the chamber, the invention may be carried out differently. For example, the windings may not be symmetrical and/or their axis of symmetry may not coincide with the center of the chamber or the workpiece center. Close concentration of the windings 144 about the center axis 146 is accomplished by vertically stacking the windings 144 in the manner of a solenoid so that they are each a minimum distance from the chamber center axis 146. This increases the product of current (I) and coil turns (N) near the chamber center axis 146 where the plasma ion density has been the weakest for short workpiece-to-ceiling heights. As a result, the RF power applied to the non-planar coil antenna 142 produces greater induction ( $d/dt$ ) [ $N \cdot I$ ] near the chamber center axis 146 (relative to the peripheral regions) and therefore greater plasma ion density in that region, so that the resulting plasma ion density is more nearly uniform despite the small workpiece-to-ceiling height. Thus, the invention provides a way for reducing the ceiling height for enhanced plasma process performance without sacrificing process uniformity.

The cylindrical chamber 140 consists of a cylindrical side wall 150 and a circular ceiling 152 which can be integrally formed with the side wall 150 so that the side wall 150 and ceiling 152 can constitute a single piece of material, such as silicon. However, the embodiment illustrated FIG. 8A has the side wall 150 and ceiling 152 formed as separate pieces. The circular ceiling 152 may be of any suitable cross-sectional shape such as planar, dome, conical, truncated conical, cylindrical or any combination of such shapes or curve of rotation. Generally, the vertical pitch of the solenoid antenna 142 (i.e., its vertical height divided by its horizontal width) exceeds the vertical pitch of the ceiling 152, even for ceilings defining 3-dimensional surfaces such as dome, conical, truncated conical and so forth. For example, the vertical pitch of the solenoid antenna 142 is several times the vertical pitch of a typical dome-shaped ceiling. Of course, the vertical pitch of the flat ceiling 152 of FIG. 8A is zero. A solenoid having a pitch exceeding that of the ceiling is referred to herein as a non-conformal solenoid, meaning that, in general, its shape does not conform with the shape of the ceiling, and more specifically that its vertical pitch exceeds the vertical pitch of the ceiling.

A pedestal 154 at the bottom of the chamber 140 supports a workpiece 156, such as a semiconductor wafer, which is to be processed. The chamber 140 is evacuated by a pump (not shown in the drawing) through an annular passage 158 to a pumping annulus 160 surrounding the lower portion of the chamber 140. The interior of the pumping annulus may be lined with a replaceable metal liner 160a. The annular passage 158 is defined by the bottom edge 150a of the cylindrical side wall 150 and the top surface of the outer silicon ring 61

surrounding. Process gas is furnished into the chamber 140 through any one or all of a variety of gas feeds. In order to control process gas flow near the workpiece center, a center gas feed 164a can extend downwardly through the center of the ceiling 152 toward the center of the workpiece 156. In order to control gas flow near the workpiece periphery, plural radial gas feeds 164b, which can be controlled independently of the center gas feed 164a, extend radially inwardly from the side wall 150 toward the workpiece periphery, or base axial gas feeds 164c extend upwardly from near the pedestal 154 toward the workpiece periphery, or ceiling axial gas feeds 164d can extend downwardly from the ceiling 152 toward the workpiece periphery. Etch rates at the workpiece center and periphery can be adjusted independently relative to one another to achieve a more radially uniform etch rate distribution across the workpiece by controlling the process gas flow rates toward the workpiece center and periphery through, respectively, the center gas feed 164a and any one of the outer gas feeds 164b-d. This feature of the invention can be carried out with the center gas feed 164a and only one of the peripheral gas feeds 164b-d.

The solenoidal coil antenna 142 is wound around a housing 166 surrounding the center gas feed 164. A plasma source RF power supply 168 is connected across the coil antenna 142 and a bias RF power supply 170 is connected to the pedestal 154.

In order that the windings 144 be at least nearly parallel to the plane of the workpiece 156, they preferably are not wound in the usual manner of a helix but, instead, are preferably wound so that each individual turn is parallel to the (horizontal) plane of the workpiece 156 except at a step or transition between turns (from one horizontal plane to the next).

Confinement of the overhead coil antenna 142 to the center region of the ceiling 152 leaves a large portion of the top surface of the ceiling 152 unoccupied and therefore available for direct contact with temperature control apparatus including, for example, plural radiant heaters 172 such as tungsten halogen lamps and a water-cooled cold plate 174 which may be formed of copper or aluminum for example, with coolant passages 174a extending therethrough. Preferably the coolant passages 174a contain a coolant of a known variety having a high thermal conductivity but a low electrical conductivity, to avoid electrically loading down the antenna or solenoid 142. The cold plate 174 provides constant cooling of the ceiling 152 while the maximum power of the radiant heaters 172 is selected so as to be able to overwhelm, if necessary, the cooling by the cold plate 174, facilitating responsive and stable temperature control of the ceiling 152. The large ceiling area irradiated by the heaters 172 provides greater uniformity and efficiency of temperature control. (It should be noted that radiant heating is not necessarily required in carrying out the invention, and the skilled worker may choose to employ an electric heating element instead, as will be

described later in this specification.) If the ceiling 152 is silicon, as disclosed in co-pending U.S. application Serial No. 08/597,577 filed February 2, 1996 by Kenneth S. Collins et al., then there is a significant advantage to be gained by thus increasing the uniformity and efficiency of the temperature control across the ceiling. Specifically, where a polymer precursor and etchant precursor process gas (e.g., a fluorocarbon gas) is employed and where the etchant (e.g., fluorine) must be scavenged, the rate of polymer deposition across the entire ceiling 152 and/or the rate at which the ceiling 152 furnishes a fluorine etchant scavenger material (silicon) into the plasma is better controlled by increasing the contact area of the ceiling 152 with the temperature control heater 172. The solenoid antenna 142 increases the available contact area on the ceiling 152 because the solenoid windings 144 are concentrated at the center axis of the ceiling 152.

The increase in available area on the ceiling 152 for thermal contact is exploited in a preferred implementation by a highly thermally conductive torus 175 (formed of a ceramic such as aluminum nitride, aluminum oxide or silicon nitride or of a non-ceramic like silicon either lightly doped or undoped) whose bottom surface rests on the ceiling 152 and whose top surface supports the cold plate 174. One feature of the torus 175 is that it displaces the cold plate 174 well-above the top of the solenoid 142. This feature substantially mitigates or nearly eliminates the reduction in inductive coupling between the solenoid 142 and the plasma which would otherwise result from a close proximity of the conductive plane of the cold plate 174 to the solenoid 142. In order to prevent such a reduction in inductive coupling, it is preferable that the distance between the cold plate 174 and the top winding of the solenoid 142 be at least a substantial fraction (e.g., one half) of the total height of the solenoid 142. Plural axial holes 175a extending through the torus 175 are spaced along two concentric circles and hold the plural radiant heaters or lamps 172 and permit them to directly irradiate the ceiling 152. For greatest lamp efficiency, the hole interior surface may be lined with a reflective (e.g., aluminum) layer. The ceiling temperature is sensed by a sensor such as a thermocouple 176 extending through one of the holes 175a not occupied by a lamp heater 172. For good thermal contact, a highly thermally conductive elastomer 173 such as silicone rubber impregnated with boron nitride is placed between the ceramic torus 175 and the copper cold plate 174 and between the ceramic torus 175 and the silicon ceiling 152.

In the embodiment of FIG. 8A, the chamber 140 may be an all-semiconductor chamber, in which case the ceiling 152 and the side wall 150 are both a semiconductor material such as silicon. RF bias power is applied separately to the semiconductor ceiling 152 and semiconductor wall 150 by respective RF power sources 1210, 1212. Controlling the temperature of, and RF bias power applied to, either the ceiling 152 or the wall

150 regulates the extent to which it furnishes fluorine scavenger precursor material (silicon) into the plasma or, alternatively, the extent to which it is coated with polymer. The material of the ceiling 152 is not limited to silicon but may be, in the alternative, silicon carbide, silicon dioxide (quartz), silicon nitride or a ceramic.

The chamber wall or ceiling 150, 152 need not be used as the source of a fluorine scavenger material. Instead, a disposable silicon member can be placed inside the chamber 140 and maintained at a sufficiently high temperature to prevent polymer condensation thereon and permit silicon material to be removed therefrom into the plasma as fluorine scavenging material. In this case, the wall 150 and ceiling 152 need not necessarily be silicon, or if they are silicon they may be maintained at a temperature (and/or RF bias) near or below the polymer condensation temperature (and/or a polymer condensation RF bias threshold) so that they are coated with polymer from the plasma so as to be protected from being consumed. While the disposable silicon member may take any appropriate form, in the embodiment of FIG. 8A the outer and inner silicon ring pieces 61, 63 may be removable and disposable expendable members of high purity silicon and may be doped to alter their electrical or optical properties. In order to maintain the silicon rings 61, 63 at a sufficient temperatures to ensure their favorable participation in the plasma process (e.g., its contribution of silicon material into the plasma for fluorine scavenging), respective sets 177a, 177b of plural radiant (e.g., tungsten halogen lamp) heaters arranged in a circle under the silicon ring 61 and over the silicon ring 63, respectively heat the respective rings 61, 63 through respective quartz windows 178a, 178b. The respective sets of heaters 177a, 177b are controlled in accordance with the temperature of the respective silicon rings 61, 63 sensed by respective temperature sensors 179a, 179b which may be remote sensors such as optical pyrometers or fluoro-optical probes. The sensors 179a, 179b may extend partially into deep holes in the respective rings 61, 63, the deepness and narrowness of the hole tending at least partially to mask temperature-dependent variations in thermal emissivity of the silicon rings 61, 63, so that they appear to behave more like gray-body radiators for more reliable temperature measurement.

As described in U.S. application Serial No. 08/597,577 referred to above, an advantage of an all-semiconductor chamber is that the plasma is free of contact with contaminant producing materials such as metal, for example. For this purpose, plasma confinement magnets 180, 182 adjacent the annular opening 158 prevent or reduce plasma flow into the pumping annulus 160. To the extent any polymer precursor and/or active species succeeds in entering the pumping annulus 160, any resulting polymer or contaminant deposits on the replaceable interior liner 160a may be prevented from re-entering the plasma chamber 140 by maintaining the liner 160a at a temperature significantly below the pol-

such as quartz that can be used for the window 64. Quartz typically is transparent between about 300 nm and 3 microns, while silicon's peak thermal emission wavelength varies from 4 microns at 400°C to 10 microns at room temperature. Thus, the range of directly measurable the silicon ring temperatures is limited, since silicon below about 200°C does not appreciably radiate within the optical passband of quartz. One solution illustrated in FIG. 4D is to employ a small port 64a within the quartz window 64, the small port 64a being of a material which is transparent at the long wavelengths emitted by silicon at cooler temperatures down to room temperature. The small port 64a can be sapphire or zinc selenide. The radiant temperature sensor 66 would be selected to be responsive at the longer wavelengths passed by the small port 64a. Alternatively, instead of the small long-wavelength port 64a within the window 64, a separate long-wavelength port 65 illustrated in FIG. 4E outside of the window 64 may be employed and may be made of sapphire or zinc selenide. The long wavelength port 65 may be replaced by its equivalent, a long wavelength version of the optical fiber 72, such as a sapphire optical fiber.

If the sensor 66 is a fluoroptical probe, then it is unaffected by the thermal emissivity of the ring 60. In this case, a fluorescent substance or powder is immersed in the surface of a small region of the ring 60 aligned with the optical fiber end 72b. An optical pulse is applied periodically to the other fiber end 72a and the resulting optical pulse-stimulated emission from the fluorescent powder (in the ring 60) travels from the fiber end 72b to the fiber end 72a to be analyzed by the sensor 66 to determine the ring temperature. A counterbore in the ring 60 shields the optical fiber end 72b from background radiation.

In order to radiantly cool the ring 60, the window 64 may be cooled by conventional means, for example by providing a cold sink for radiant cooling of the polymer-hardening precursor ring 60. In this case, the rate at which the polymer-hardening precursor ring 60 is cooled is a function of  $[T_{ring}]^4 - [T_{window}]^4$ , where  $T_{ring}$  and  $T_{window}$  are the absolute temperatures (Kelvin), respectively, of the polymer-hardening precursor ring 60 and the cooled window 64. Efficient radiant cooling of the ring 60 is attained by maintaining a 200°C temperature difference between the silicon ring 60 and the window 64, which is readily accomplished by conventional liquid or gas cooling apparatus 67 in contact with the window 64, provided the ring 60 is maintained within the preferred temperature range of 300°C and 700°C. However, the ring may instead be cooled using any one of a number of conventional techniques. For example, it may be cooled in the manner that the wafer is typically cooled.

Whether the ring 60 is conductively cooled by a conventional cold plate or is radiantly cooled by the window 64, in some cases it may not be necessary to provide a heat source (such as the tungsten halogen lamps). Instead, heating by the plasma itself may be more than

sufficient to heat the ring 60, in conjunction with the conductive or radiant cooling, to maintain stable temperature control of the ring 60 within the requisite temperature range. Thus, in an alternative embodiment, no heat source is provided.

In the embodiment of FIG. 6, the inductive heating coil 62 is replaced by a radiant heater 80 such as a tungsten-halogen lamp or an electric discharge lamp which emits electromagnetic radiation of a wavelength within the optical transmission band of the quartz window 64 (to avoid heating the window 64) and within the absorption band of the polymer-hardening precursor ring 60. Preferably, the wavelength of the emission from the radiant heater 80 differs from the wavelength of the emission from the polymer-hardening precursor ring 60 in order to avoid interfering with the temperature measurement performed by the optical pyrometer 66. However, if the optical fiber 72 is sunk into the counterbore 60a and if the optical fiber is completely shielded by the opaque shield 72c that extends down to the top of the counterbore 60a, then the radiant heater emission cannot interfere with the temperature measurement, and so it is not required, in this case, that the radiant heater emission wavelength differ from the emission wavelength of the (silicon) ring 60. In fact, this is advantageous since a number of commercially available detectors that could be installed at the output end of the optical fiber are more stable near the short emission wavelength range (1-2μ) of silicon. In this case, the temperature measurement is performed at shorter wavelengths so that the long wavelength port 64a or 65 or long wavelength (e.g., sapphire) optical fiber is not required.

To summarize the requirements for optimum radiant heating and radiant temperature sensing: (a) the material of the window 64 is highly transmissive at the wavelength of the radiant heat source 80 and either the window 64 itself or a small assigned portion of it or an optical fiber through it is highly transmissive at the wavelength to which the temperature sensor 66 is responsive but is not itself highly radiant at that wavelength; (b) the polymer-hardening precursor ring 60 is highly absorbing at the wavelength of the radiant heater 80 and either the ring 60 itself or a material embedded in or on it is radiant at the wavelength at which the sensor 66 responds; and (c) the wavelength of the radiant heater 80 does not coincide with the wavelength at which the sensor 66 is responsive and yet lies within the absorption spectrum of the polymer precursor ring 60 and outside the absorption spectrum of the window 64.

The foregoing requirements can be met in various ways, for example by first specifying the materials of the polymer-hardening precursor ring 60 and then selecting a compatible material for the window 64 and then finally selecting the wavelengths of the radiant heater and the sensor 66 by process of elimination, or else specifying the wavelengths of the sensor 66 and the radiant heater and then selecting the materials by process of elimination.

tion. The foregoing requirements may be relaxed to an extent depending upon the sensitivity of the temperature measurement and temperature control precision desired.

If radiant cooling is desired, then further requirements are imposed upon the window 64: (a) in the portion of the window 64 through which the sensor 66 views the ring 60 the window 64 is at least nearly transparent to the wavelength of radiation emitted by the heated ring 60 (as stated above), while (b) in other portions of the window 64 not used by the sensor 66 to view the ring 60 the window 64 has an absorption spectrum which includes the re-radiation wavelength of the radiantly heated polymer-hardening precursor ring 60, so as to absorb heat therefrom to provide radiant cooling.

One way of reducing the number simultaneous constraints on the material of the window 64 is to not require the window 64 to transmit both heat to the ring 60 and the ring's thermal emission to the sensor 66. This is accomplished by employing the small long-wavelength (zinc selenide or sapphire) port 64a or auxiliary window 65 for exclusive use by the sensor 66 or to employ the optical fiber 72 for exclusive use by the sensor 66, in either case reducing the function of the window 64 to transmitting radiation from the heat source only. In this case, if radiant cooling is desired, then the only other constraint on the window is that it absorb emission from the ring 60. This is possible as long as the emission wavelength of the radiant heat source 80 and the ring emission are of different wavelengths. Furthermore, it is preferred that the sensor 66 is not responsive at the wavelengths emitted by the radiant heat source 80.

In one working example, the polymer-hardening precursor ring 60 was crystalline silicon with a resistivity of 0.01  $\Omega$ -cm and an average emissivity between 0.3 and 0.7, the window 64 was quartz with an optical pass-band between 300 nm and 3 microns, the sensor 66 was an optical pyrometer that sensed radiation through an optical fiber (corresponding to the optical fiber 72) in a wavelength range of 4-10 microns and the radiant heater 80 was a 3000°K tungsten-halogen lamp with a peak power emission wavelength range of 0.9-1.0 micron. It should be noted that optical pyrometry in either a visible or non-visible wavelength range may be employed in carrying out the invention.

Referring now to a preferred embodiment illustrated in FIG. 7, an expendable polymer-hardening precursor ring 60 of silicon is added to the all-semiconductor (silicon) reactor chamber of FIG. 3 and heated by a heating device 90 which may be either an induction heater or a radiant heater. Optionally, and in addition, a separate RF bias source 400 may be connected to the ring 60 to help, along with the heating of the ring 60, to maintain the ring 60 reactive with the plasma and furnish polymer-hardening precursor material therefrom into the plasma. The advantage is that none of the silicon window electrodes (e.g., the silicon side wall 12 or the silicon ceiling 14) are used to provide silicon to the polymer chemistry

and therefore they need not be heated to the elevated temperatures (e.g., over 200°C to 700°C) to which a polymer-hardening precursor must be heated. Moreover, the RF bias power applied to the silicon wall 12 and the silicon ceiling 14 need not be so high as to promote consumption of the silicon material thereof. In fact, it may be preferable to apply no bias to the walls and ceiling. Preferably, the temperature of the silicon ceiling 14 and of the silicon side wall 12 and the RF power applied thereto are selected to minimize consumption thereof by etching, sputtering or ion bombardment thereof while maintaining their surfaces relatively free of polymer accumulation, to avoid frequent chamber cleaning operations. The best mode for accomplishing this is the light deposition mode referred to later in this specification. In a light deposition mode carried out during a two-minute plasma etch/polymer deposition process, the silicon wall temperature is maintained near 100°C-150°C, and the resulting polymer deposition thereon is sufficiently light so that it can be removed subsequently by a 10 to 20 second exposure to a high density oxygen plasma temporarily generated in the chamber following etching of the wafer. Alternatively, but not preferably, a heavy deposition mode may be employed in which the silicon chamber walls are held near room temperature (for example) during the etch process.

Referring to FIG. 8A, separate independently controllable polymer-hardening precursor rings 61, 63 are placed at different radial locations relative to the wafer to permit further compensation for radially non-uniform processing conditions. The separate outer and inner polymer-hardening precursor rings 61, 63 of FIG. 8A are independently controlled by respective temperature controllers 68a, 68b in a manner described below in this specification. In order to compensate for processing conditions giving rise to different etch selectivities at different radial locations on the wafer 17, the user may select different polymer-hardening precursor ring temperatures to be maintained by the different temperature controllers 68a, 68b.

While any suitable reactor configuration may be employed in carrying out an embodiment having the separately controlled outer and inner polymer-hardening precursor rings 61, 63, the implementation illustrated in FIG. 8A employs a reactor having a solenoidal antenna over a heated semiconductor window electrode ceiling of the type disclosed in above-referenced co-pending U.S. application Serial No. \_\_\_\_ by Kenneth S. Collins et al. entitled "Inductively Coupled RF Plasma Reactor Having Overhead Solenoidal Antenna". Notably, the presently preferred implementation of the present invention employs the reactor of the above-referenced co-pending application but with only the outer polymer-hardening precursor ring 61. The reactor of the above-referenced co-pending application includes a cylindrical chamber 140 having a non-planar coil antenna 142 whose windings 144 are closely concentrated in non-planar fashion near the center axis 146 of the cylindrical

coupling from other chamber surfaces having RF power applied directly thereto.) Because the ceiling 14 (and/or side wall 12) is integrated with the temperature control system described above, its replacement entails loss of productivity due to the amount of labor required to remove and replace it, as well as a cost to acquire a new silicon ceiling 14 connectable to the temperature control apparatus. The present invention solves this problem because the process of the invention can further include reducing the RF bias applied by the RF power source 20 to the ceiling 14 (or reducing the RF power applied by the RF power source 22 to the silicon side wall of FIG. 3) while further increasing the silicon ceiling (and/or side wall) temperature to compensate for the reduction in RF bias power. The advantage of this latter feature is that the rate at which silicon is removed from the ceiling 14 (and/or side wall 12) is reduced with the reduction in applied RF power to the ceiling. In one example, the RF power applied by the RF power source 20 to the ceiling 14 may be reduced four-fold while the temperature of the ceiling 14 is increased only moderately from about 200°C to about 240°C. Thus, the invention provides dual advantages of (a) revolutionary improvement in polymer resistance to etching and (b) reduced consumption rate of the silicon material in the ceiling or side wall. The increased polymer durability results in an increased etch selectivity while the decreased silicon consumption rate results in decreased cost of operation and decreased loss in productivity.

Even though the invention permits a reduction in consumption rate of the polymer-hardening precursor piece (e.g., the silicon ceiling), its replacement is nevertheless expensive and time-consuming due at least in part to its integration with the temperature control apparatus for maintaining the requisite temperature of the piece in accordance with the polymer-hardening process of the present invention. However, the invention is preferably carried out with a separate cheaply fabricated quickly replaceable polymer-hardening precursor piece, to avoid consuming any of the integral parts of the reactor chamber such as the chamber side wall or the chamber ceiling. Such a replaceable polymer-hardening precursor piece can be of any suitable easily fabricated shape (e.g., planar annulus, planar ring, solid ring, cylinder, plate, and so forth) and placed at any suitable location within the reactor chamber. However, in the embodiment of FIG. 4A, the expendable polymer-hardening precursor piece is a thin planar annular ring 60 of a polymer-hardening precursor material (such as silicon) surrounding a peripheral portion of the wafer pedestal 16. While the ring 60 can lie in any suitable plane within the chamber, in order to permit access to the wafer by a conventional wafer transfer mechanism the silicon ring 60 lies slightly below or nearly in the plane of the wafer 17 held on the wafer pedestal 16.

In order to eliminate any necessity of integrating or mechanically coupling the polymer-hardening precursor ring 60 with a direct temperature control apparatus,

heating by a method other than direct conduction (e.g. radiant heating or inductive heating) is preferably employed. A radiant heat source such as a tungsten halogen lamp or an electric discharge lamp may be employed. A radiant or inductive heat source can be internal --unseparated from the ring 60, or it can be external --separated from the ring 60 by a transmissive window for example. In the embodiment of FIG. 4A, an external inductive heater is employed constituting an inductive coil 62 separated from the polymer-hardening precursor ring 60 by a window 64 of a material such as quartz which is at least nearly transparent for purposes of inductive coupling. In order to provide the most efficient inductive heating, the polymer-hardening precursor ring 60 is formed of silicon having a sufficiently low resistivity, for example on the order of 0.01 Ω-cm. The following is an example illustrating how to select the resistivity of a silicon version of the ring 60. If: (a) the thickness T of the ring 60 must be about 0.6 cm (0.25 in) for structural-mechanical purposes, (b) the inductive heater coil 62 is driven at a frequency of 1.8 MHz, (c) an RF skin depth  $\delta = \Gamma T$  (for example,  $\Gamma=1$ ) is desired for optimum absorption efficiency, and (d) the silicon ring 60 has a magnetic permeability  $\mu$ , then the maximum resistivity of the silicon ring 60 is given by:

$$\rho = \delta^2 \cdot \pi \cdot f \cdot \mu$$

which in the foregoing example is 0.029 Ω-cm. The present invention has been implemented using 0.01 Ω-cm silicon. In the case of a semiconductor such as silicon, there is no risk of falling short of the minimum resistivity in this case and so no computation of the minimum resistivity is given here.

In a working example corresponding to the embodiment of FIG. 4A, 4000 Watts of source power at 2.0 MHz was applied to the inductive coil 18, 1400 Watts of bias power at 1.8 MHz was applied to the wafer pedestal 16, process gases of CHF<sub>3</sub> and CO<sub>2</sub> were introduced into the reactor chamber at flow rates of 120 sccm and 46 sccm, respectively, while the chamber pressure was maintained at 50 mTorr, the ceiling temperature was maintained at 200°C and the side wall temperature was maintained at 220°C. The polymer-hardening precursor ring 60 was crystalline silicon and reached a temperature in the range of between 240°C and 500°C. The polymer deposited onto the silicon and polysilicon surfaces on the wafer 17 was characterized by the shinier appearance of a polymer hardened by the process of the present invention.

The semiconductor wafer 17 processed in this working example had the multi-layer conductor structure illustrated in FIG. 4B consisting of a silicon substrate 17a, a silicon dioxide layer 17b and a polysilicon conductor line 17c, the etch process being facilitated by a photoresist layer 17d having mask openings 17e, 17f defining the openings 17g, 17h etched through the sili-

con dioxide layer 17b down to the polysilicon conductor 17c and the substrate 17a, respectively. A very high oxide-to-silicon etch selectivity is necessary to prevent the punchthrough, depending upon the ratio between the depths of the silicon substrate and the intermediate polysilicon layer through the silicon oxide. For the case in which the deep contact opening 17h through the oxide to the substrate is 1.0 micron deep and is to be 50% overetched, the intermediate contact opening 17g to the polysilicon layer is 0.4 microns deep and not more than 0.01 microns of the intermediate polysilicon conductor layer 17c are to be removed (to avoid punch-through), then an oxide-to-silicon etch selectivity of at least 110:1 is required.

By increasing the temperature of the silicon ring 60 over the processing of successive wafers, it was found that oxide-to-silicon etch selectivity generally increased with temperature in the manner illustrated in the graph of FIG. 5A. The two data points A and B of FIG. 5A correspond to the curves A and B of FIG. 5B illustrating radial distribution of the polysilicon etch rate in angstroms/minute at temperatures of 240°C and 500°C, respectively. The etch selectivities of data points A and B of FIG. 5A were computed from the oxide etch rate of 9,000 angstroms/minute observed at both temperatures as an etch selectivity of 30:1 at 240°C and 150:1 at 500°C. Thus, increasing the temperature to 500°C provides a selectivity well-above the 110:1 minimum selectivity required in the above-given working example of FIG. 4B.

In the embodiment of FIG. 4A, the temperature of the polymer-hardening precursor ring 60 is sensed by a temperature-sensing device 66 which is not attached to the silicon ring 60. A controller 68 governing the current or power flow through the inductor 62 monitors the output of the temperature-sensing device 66 in order to maintain the temperature of the polymer-hardening precursor ring 60 at the desired temperature. Preferably, the temperature-sensing device 66 is a radiant temperature sensor which responds to radiation from the ring 60 within a particular wavelength range. Such a radiant temperature sensor may be an optical pyrometer responsive to thermal radiation or a fluoro-optical probe which responds to optical pulse-stimulated emission. For this purpose, the window 64 is of a material which is at least sufficiently transmissive within the wavelength range of the sensor 66 to provide an optical signal-to-noise ratio adequate to enable temperature control of the ring 60. Preferably, and in addition, the material of the window 64 (over its range of operating temperatures) does not thermally radiate strongly (relative to the radiation from the silicon ring 60) within the wavelength range of the sensor 66, so that the radiation of the window 64 is practically invisible to the sensor 66 so as to not interfere with its measurement of the silicon ring temperature.

If the polymer-hardening precursor ring 60 is silicon, then one difficulty in measuring its temperature by an

optical pyrometer is that the thermal emissivity of silicon varies with temperature. (The silicon emissivity also happens to vary with wavelength and doping level, although it is the temperature dependence of the emissivity that is addressed here.) One solution to this problem

- 5 is to bond a small piece 70 of a black-body or gray-body radiating material such as silicon nitride to the ring 60. Preferably an optical fiber 72 (indicated in dashed line) is placed with one end 72a facing a sensing portion 74 of the sensor 66 and the other end 72b facing the gray-body radiator piece 70 bonded to the ring 60. (If a black-body or gray-body radiating material is not added, then the long-wavelength radiation emitted by the silicon ring 60 at lower (e.g., room) temperatures can be carried by
- 10 the optical fiber 72 provided the fiber 72 is a long wavelength material such as sapphire or zinc selenide in lieu of the usual optical fiber material of quartz.) Since the temperature measurement by the sensor 66 can be degraded by background radiation from the plasma, it is
- 15 preferred to provide a counter-bore 60a in the ring 60 to shield the optical fiber end 72b from background radiation (e.g., from heated chamber surfaces and from the plasma itself) without requiring any contact between the optical fiber 72 and the ring 60. In addition to or instead
- 20 of providing the counter-bore 60a to shield the optical fiber end 72b from plasma or background radiation, the wavelength of the sensor 66 can be selected to lie outside the plasma emission band (4 microns to 8 microns).
- 25 The optical fiber 72 may be employed with or without the gray-body radiator piece 70. The window 64 passes heat to the ring 60 while the optical fiber 72 passes emission from the ring 60 to the temperature sensor 66.

If the temperature measurement is made directly of the silicon (i.e., without the intervening gray-body radiator piece 70), then it is preferable to use a material such as sapphire for the optical fiber 72 which is highly transmissive at the emission wavelength of silicon, and to shield the optical fiber 72 with an opaque shield. Moreover, the problem of the silicon's emissivity varying with

- 30 temperature may be ameliorated as shown in FIG. 4C by providing, in registration with the counterbore 60a, a hole 60b which is a relatively deep and narrow with a high (e.g., 5:1) aspect ratio, the optical fiber 72 being sunk into the counterbore 60a to prevent background
- 35 optical noise from entering the fiber end and an opaque shield 72c surrounding the remainder of the optical fiber 72. Such a deep hole may extend axially in the silicon ring 60 but preferably it extends radially from the circumferential edge of the silicon ring 60. In this implementation, virtually none of the optical radiation from a heater lamp or from the plasma itself can enter the optical fiber 72 to interfere with the temperature measurement.

If the ring temperature is to be sensed through the window 64 in the absence of the optical fiber 72, then another difficulty with measuring the temperature of the silicon ring 60 is that below 200°C its peak thermal emission wavelength is shifted to a very long wavelength, well outside the optical passband of typical materials

(polymerization temperature)

FIG. 1 is a simplified cut-away side view of a plasma reactor of the type disclosed in a first one of the co-pending applications referred to above.

FIG. 2 is a simplified cut-away side view of a plasma reactor of the type disclosed in a second one of the co-pending applications referred to above.

FIG. 3 is a simplified cut-away side view of a plasma reactor of the type disclosed in a third one of the co-pending applications referred to above.

FIG. 4A is a cut-away side view of a plasma reactor in accordance with a preferred embodiment of the present invention employing inductive heating of an expendable polymer-hardening precursor piece.

FIG. 4B is an enlarged cross-sectional view of the workpiece processed in a working example of the embodiment of FIG. 4A, illustrating the multi-layer conductor structure of the workpiece.

FIG. 4C is an enlarged view corresponding to FIG. 4A illustrating a sleeve and counterbore in which an optical fiber is inserted.

FIG. 4D is an enlarged view corresponding to FIG. 4A illustrating a long wavelength optical window inside a heat transparent window.

FIG. 4E is an enlarged view corresponding to FIG. 4A illustrating a long wavelength window separate from a heat transparent window.

FIG. 5A is a graph illustrating oxide-to-silicon etch selectivity as a function of temperature of a polymer-hardening precursor ring.

FIG. 5B is a graph illustrating radial distribution of the polysilicon etch rate in angstroms/minute at temperatures of 240°C and 500°C, respectively.

FIG. 6 is a cut-away view of a plasma reactor in accordance with another preferred embodiment of the invention employing radiant or infrared heating of an expendable polymer-hardening precursor piece.

FIG. 7 is a cut-away view of a plasma reactor in accordance with a preferred embodiment of the invention in which an expendable polymer-hardening precursor piece is heated in an all-semiconductor reactor chamber.

FIG. 8A is a cut-away side view of a plasma reactor in accordance with a preferred embodiment employing heated polymer-hardening precursor pieces at separate radial locations relative to the wafer being processed.

FIG. 8B corresponds to the embodiment of FIG. 8A in which the ceiling is divided into inner and outer portions.

FIG. 9 illustrates an embodiment of the invention in which the expendable polymer-hardening precursor piece is a removable liner abutting the cylindrical chamber side wall.

FIG. 10 is a graph illustrating the performance of a working example of a temperature control system in a reactor embodying the invention.

FIG. 11 is a graph illustrating the closed loop response of the temperature system whose performance

is depicted in FIG. 10

FIG. 12 is an enlarged view of a portion of the graph of FIG. 11.

Referring to FIG. 1, the above-referenced co-pend-

5 ing U.S. application Serial No. 08/580,026 discloses a plasma reactor chamber 10 having a cylindrical side wall 12, a flat ceiling 14, a wafer support pedestal 16 for supporting a workpiece 17 being processed such as a semiconductor wafer, an inductive side coil 18 wound around the cylindrical side wall 12 and independent RF power sources 20, 22, 24 connected to the ceiling 14, the pedestal 16 and the inductive coil 18, respectively. In particular, the co-pending application of Collins et al. discloses that the ceiling 14 may comprise silicon in order to provide a fluorine scavenger. For this purpose, RF power is applied to the silicon ceiling 14 by the RF power source 20 to enhance the removal of silicon therefrom.

Referring to FIG. 2, the above-referenced co-pend-

20 ing application by Rice et al. discloses that the side wall 12 is quartz and provides a temperature control system for controlling the temperature of the quartz side wall 12 and the temperature of the silicon ceiling 14. The temperature control system includes a cooling source 30 and heating source 32 coupled to the quartz side wall 12 and a cooling source 34 and heating source 36 coupled to the silicon ceiling 14. Temperature sensors 38, 40 coupled to the side wall 12 and ceiling 14, respectively, are monitored by controllers 42, 44, respectively.

25 The controller 42 governs the cooling source 30 and heating source 32 of the quartz side wall 12 while the controller 44 governs the cooling source 34 and heating source 36 of the silicon ceiling 14. The purpose for controlling the temperature of the silicon ceiling 14 is, at least in part, to prevent polymer accumulation on the ceiling 14 which would otherwise prevent the ceiling 14 from donating scavenger silicon to the plasma. Therefore, controller 44 maintains the ceiling temperature somewhat above the polymer condensation (or polymerization)

30 temperature, or about 170°C depending upon processing conditions. At the same time, the RF power source 20 applies sufficient RF power to the silicon ceiling 14 in order to promote removal of silicon from the ceiling 14 by the plasma at a sufficient rate to scavenge the

35 desired amount of fluorine for enriching the carbon content of the polymer formed on the wafer to enhance etch selectivity. In fact, the combination of elevated temperature and applied RF bias overcomes the energy threshold below which interaction between the plasma and the

40 ceiling 14 causes polymer deposition and above which the interaction causes etching of the ceiling 14.

Referring to FIG. 3, the above-referenced co-pend-

45 ing application Serial No. 08/597,577 by Kenneth S. Collins discloses that both the ceiling 14 and the side wall 12 are a semiconductor such as silicon and that they can act as windows to permit inductive coupling of RF source power through themselves to the plasma. For this reason, either one or both the side coil 18 and an

overhead inductor 50 may be employed and couple RF source power to the plasma through the silicon side wall 12 and the silicon ceiling 14. U.S. application Serial No. 08/597,577 disclosed a planar overhead coil and such would be suitable for carrying out the present invention. However, the overhead inductor 50 of the embodiment of FIG. 3 includes inner and outer solenoids 50a, 50b (of the type disclosed in above-referenced co-pending U.S. application Serial No. \_\_\_\_ by Kenneth S. Collins et al. entitled "Inductively Coupled RF Plasma Reactor Having Overhead Solenoidal Antenna") separately powered by independent RF power sources 52a, 52b to facilitate process uniformity control. Furthermore, both the ceiling 14 and side wall 12 can be employed as separate electrodes, so that RF power is applied to the silicon side wall 12 by a separate RF power source 54. Sufficient RF power is applied to either or both the silicon ceiling 14 and the silicon side wall 12 to promote removal of silicon therefrom for scavenging fluorine. The side wall 12 and ceiling 14 are preferably maintained above the polymer condensation temperature to permit their use as silicon scavenger precursors and to avoid the usual requirement for frequent chamber cleaning operations to remove polymer and associated contaminant deposits.

A first embodiment of the present invention is a process which does not merely enrich the carbon content of the carbon-fluorine polymer, but actually forms a different kind of polymer which more strongly adheres to the underlying silicon, polysilicon or similar non-oxygen-containing surfaces to be protected. The result is a revolutionary improvement in etch selectivity. It is a discovery of the invention that certain materials in a class including silicon, silicon carbide, graphite, silicon nitride, when raised to a higher temperature range (e.g., well above the polymer condensation temperature) become polymer-hardening precursors in which they change the chemical structure of the polymer, resulting in a polymer which is far more resistant to etching than has been provided in the prior art. The process is carried out by maintaining the temperature of a polymer-hardening precursor material inside the reactor chamber at a higher temperature range (e.g., 180°C to 220°C for a silicon precursor material whose potential is floating and in any case substantially above the applicable polymer condensation temperature). This higher temperature range varies greatly with the applied RF bias potential on the polymer-hardening precursor material and with the selection of the material itself.

In a second embodiment of the invention, the polymer-hardening precursor material is held in a maximum temperature range at which an even greater polymer hardness is achieved. The maximum temperature range for a silicon precursor material held at a floating potential is above 220°C and is preferably in the range from about 300°C to about 700°C. This maximum temperature range varies greatly with the RF bias applied to the polymer-hardening precursor material. While not neces-

sarily subscribing to any particular theory in this specification, it is felt that, in some case but not necessarily all, at the maximum temperature range of the polymer-hardening precursor material, the polymer-hardening precursor (e.g., silicon) material removed therefrom by the plasma bonds with the fluorine, carbon and hydrogen atoms (assuming a fluorohydrocarbon gas is employed) as they polymerize, the material (e.g., silicon) thus added providing a different kind of polymer having an optimum resistance to etching. In some cases, the polymer thus produced in this second embodiment is distinguished by a shiny surface.

At the higher temperature range, the heated polymer-hardening precursor material (e.g., in the silicon ceiling 14 in the present example): (1) reduces free fluorine in the plasma by providing scavenging fluorine to the plasma, (2) changes the relative concentrations of carbon to fluorine and hydrogen in the plasma, (3) changes the relative concentrations of etchant species and polymer precursor species in the plasma near the wafer surface. At the maximum temperature range, the heated polymer-hardening precursor material performs (1)-(3) above and (4) contributes polymer-hardening precursor (silicon) material into the polymer, producing a polymer having a resistance to etching beyond what has been heretofore attained in the art.

Efficacy of the invention is seen, for example, in the photoresist selectivity achieved by the invention, although similar improvement in silicon-to-silicon oxide selectivity is also achieved (as described later in this specification). When the polymer hardening precursor material (silicon) is heated to 300°C, sputtering effects are observed at the photoresist facets or corners of features covered by photoresist, and the etch selectivity of oxide to photoresist (the "photoresist selectivity") is only about 3:1. If the polymer hardening precursor material is heated further to about 430°C, then the photoresist selectivity jumps to about 5:1, a significant improvement. If the polymer hardening precursor material temperature is increased even further to about 560°C, then the photoresist selectivity increases to about 6:1.

Carrying out the invention in the reactor chamber of FIG. 1, 2 or 3 can be accomplished by employing the silicon ceiling 14 or silicon side wall or skirt 12 as the polymer-hardening precursor material and increasing the temperature of the silicon ceiling 14 of FIGS. 1, 2 or 3 (and/or the silicon side wall 12 of FIG. 3) to the requisite temperature. The silicon ceiling 14 (and/or silicon side wall 12), when heated to the higher temperature range of the present invention, becomes a polymer-hardening precursor.

One problem in using the silicon ceiling 14 (or silicon side wall 12) as a fluorine scavenger precursor is that it is consumed at a rate determined at least in part by the amount of RF power coupled to it and must therefore be replaced at more frequent intervals. (RF power can be coupled to the scavenger precursor either directly from an RF power generator or indirectly by capacitive

piece (e.g., a silicon ceiling) is relatively expensive. In U.S. application Serial No. 08/597,577 referenced above, an all-silicon reactor chamber is disclosed in which the walls and ceiling are silicon, and any fluorine scavenging is done by consuming the silicon ceiling or walls, requiring their replacement at periodic intervals with a concomitant increase in cost of operation and decrease in productivity. Thus, not only is it desirable to increase the polymer strength but it is also desirable to decrease the rate at which silicon must be removed from the scavenger to achieve a desired etch selectivity.

It is a discovery of the invention that by raising the temperature of a polymer hardening precursor material such as silicon inside the reactor chamber beyond that required to merely scavenge fluorine --i.e., into a higher temperature range, a different more durable polymer is formed over exposed silicon and polysilicon surfaces which is more resistant to etching than has been possible heretofore by merely scavenging fluorine. In this respect, the term "polymer hardening precursor" refers to a material in the chamber which, when its temperature is increased, increases the resistance to etching of the polymer formed on the wafer in accordance with the temperature increase. The polymer formed by holding the polymer-hardening precursor material at the higher temperature range is more durable than polymer formed otherwise, and protects the silicon and polysilicon surfaces so much better that oxide-to-silicon etch selectivity is substantially enhanced over that attained heretofore. Material from the heated polymer-hardening precursor (e.g., silicon) piece participates favorably in the polymerization process by changing the process gas content ratios of carbon-to-fluorine, hydrogen-to-fluorine and carbon-to-hydrogen as a function of its increased temperature, so that the resulting polymer is substantially strengthened. As the polymer-hardening precursor piece in the reactor chamber is heated above the polymerization temperature (the temperature below which polymer precursor materials can condense onto the surface) and into the higher temperature range, the etch selectivity increases with the temperature increase. Thus, a general method of the invention is to provide a polymer-hardening precursor piece (such as silicon, carbon, silicon carbide or silicon nitride, but preferably silicon) within the reactor chamber during an etch process with a fluoro-carbon or fluoro-hydrocarbon gas, and to heat the polymer-hardening precursor piece above the polymerization temperature sufficiently (i.e., into the higher temperature range) to achieve a desired increase in oxide-to-silicon etch selectivity beyond that heretofore attained.

In accordance with an alternative embodiment of the invention, it is a discovery of the invention that the temperature of the polymer-hardening precursor material can be increased even further into a maximum temperature range at which the hardness of the resulting polymer is even greater. In some cases, this is indicated by a shiny appearance of the polymer. It is believed that

in this maximum temperature range, material from the polymer-hardening precursor piece enters into the polymer to achieve the extremely hard polymer. For example, if the polymer-hardening precursor material is silicon and is held at this maximum temperature range, then the resulting polymer on the wafer contains silicon.

The higher temperature range of the first embodiment and the maximum temperature range of the second embodiment depend upon the RF bias applied to the polymer-hardening precursor piece. In the absence of an external applied RF bias or potential on a polymer-hardening precursor piece of crystalline silicon, the higher temperature range was about 100°C to about 220°C while the maximum temperature range was above 220°C and preferably between 300°C and 700°C. However, any directly or indirectly applied RF bias power quickly shifts such temperature range downwardly.

The polymer-hardening precursor (e.g., silicon) piece may be an integral part of the reactor chamber walls and/or ceiling. However, it is preferably a separate, expendable and quickly removable piece, and the heating/cooling apparatus may be of any suitable type including apparatus which conductively or remotely heats the polymer-hardening precursor piece. Alternatively, if plasma heating of the polymer-hardening precursor piece is sufficient, the desired effect is achieved by refraining from cooling the polymer-hardening precursor piece so as to maintain it at least in the higher temperature range (i.e., above the polymerization temperature). In this alternative mode, the requisite heating of the polymer-hardening precursor piece is accomplished by exploiting plasma heating in lieu of conduction heating apparatus mechanically coupled to the polymer-hardening precursor piece.

In accordance with a preferred embodiment of the invention, no heating apparatus is directly or mechanically coupled to the polymer-hardening precursor piece, thereby permitting the piece to be cheaply fabricated and quickly removable from the reactor chamber. In this form, the polymer-hardening precursor piece is a simply-shaped expendable item in the reactor chamber separate from the chamber structural features such as the wall and ceiling, and has no mechanical features for coupling to other apparatus such as heating devices. Preferably, the heating apparatus heats the polymer-hardening precursor piece by radiation or induction rather than conduction to avoid mechanical coupling therewith, so as to be unaffected by removal and replacement of the expendable piece and so as to be free from temperature sensitivity to mechanical connections. Also, where cooling of the silicon piece is required, it is preferred to employ radiant cooling to avoid mechanical coupling. Similarly, temperature control is achieved by remotely (e.g., by re-radiation as with an optical pyrometric temperature probe or by stimulated emission as with a fluoro-optical temperature probe) sensing the silicon piece temperature, so that no temperature sensor

apparatus is mechanically coupled to the silicon piece. Thus, a preferred embodiment employs radiant (or inductive) heating, radiant cooling, and remote temperature sensing of the polymer-hardening precursor piece to eliminate sensitivity of the temperature control to mechanical contact.

Remote temperature sensing of the polymer-hardening precursor piece can be performed using devices such as an optical pyrometer or a fluoro-optic probe. An advantage of the latter is that it is independent of the thermal emissivity of the material being measured.

In one aspect of the invention, the silicon piece functions not only as a polymer hardening precursor material but also as a shield between the heat source and the plasma source region preventing the heat source (e.g., a radiant or inductive heater) from generating plasma. It also shields the heat source (or its window) from exposure to the plasma or its corrosive effects.

In a preferred implementation, the expendable polymer-hardening precursor piece is a planar silicon annulus or base plate extending radially outwardly from a circumferential periphery of the wafer support or wafer chuck toward the chamber sidewall. (Further, if desired the silicon base plate may serve as a heat shield to protect from the plasma an underlying ceramic clamp (or electrostatic chuck) holding the wafer on the wafer pedestal used in certain types of plasma reactors.) In the preferred implementation, the silicon base plate is heated through inductive heating by an underlying inductor, although any other suitable remote heating technique may be employed, such as infrared radiation heating. For this purpose, silicon material of an appropriate resistivity is selected for the heated silicon piece to assure efficient inductive heating thereof by the underlying inductor and at least nearly complete absorption of the induction field so that the silicon piece functions as a plasma shield as well as a heat shield. The temperature control system monitors the silicon base plate temperature using a radiant temperature sensor facing the silicon piece through a radiantly transparent window, or through a window which is at least nearly transparent at a wavelength range within which the temperature sensor responds. In one implementation, the radiantly transmissive window is quartz, the sensor is an optical pyrometer, and a small black-body radiator piece or gray-body radiator piece, such as a small piece of silicon nitride, is bonded to a location on the silicon base plate viewed by the temperature sensor to enhance the sensor's performance.

If the present invention is employed (for example, in the form of the radiantly heated silicon baseplate) in the all-silicon reactor chamber of U.S. application Serial No. 08/597,577 referred to above, then the walls of the all-silicon reactor are operated in a "light deposition" mode rather than in an etch mode so as to not consume (or at least to reduce the rate of consumption of) the silicon side wall or skirt and the silicon ceiling. Thus, what is chiefly consumed is the inexpensive and quickly

replaceable silicon base plate. This is best accomplished by reducing the temperature of the silicon side wall or skirt and silicon ceiling and reducing or eliminating the RF bias applied thereto (e.g. by grounding the wall, skirt and/or ceiling). Preferably, the temperature of the silicon wall and silicon ceiling and the RF bias thereon is reduced to a point at which consumption thereof is minimized by permitting a light polymer deposition thereon, but not beyond a point at which polymer deposition thereon becomes dense and difficult to remove. Such a lightly deposited polymer can be quickly and easily removed by a plasma clean step. This preserves a major advantage of the all-silicon reactor chamber in avoiding or minimizing the necessity of frequent chamber cleanings, as described in the above-referenced application. Alternatively, but not preferably, a "heavy deposition mode" may be selected which permits a heavy polymer deposition onto the silicon wall and ceiling.

In accordance with another embodiment of the invention, separately expendable silicon pieces are disposed at different radial locations relative to the wafer being processed in order to enable independent control of etch selectivity over different radial portions of the wafer. This embodiment may be combined with the features of separately controllable inductors at respective radial locations and separately controllable electrodes at respective radial locations disclosed in co-pending U. S. application Serial No. 08/597, 577 referred to above.

It is a further discovery of the invention that the polymer-hardening precursor function fulfilled by the silicon piece requiring the elevated temperature described above does not imply a concomitantly elevated consumption rate. Where the silicon piece is not an expendable item in the reactor (or even if it is), its rate of consumption can be reduced to save cost while preserving its polymer-hardening function above the polymerization temperature. This is accomplished by reducing the RF bias applied to the silicon piece while further increasing the temperature thereof to compensate for the decrease in RF bias and thereby maintain its polymer-hardening participation in the process. In accordance with one implementation, the RF bias thereon can be decreased four-fold for a dramatic decrease in consumption rate while increasing the silicon piece temperature by only about 25% to maintain the polymer-hardening function. Preferably, the temperature is increased until the applied RF bias can be eliminated entirely.

While the preferred material employed in the various embodiments of the polymer-hardening precursor referred to above is silicon, any other suitable material whose contribution to the polymer hardness is achieved by heating a piece of it in the reactor may be employed in the foregoing embodiments. In addition to silicon, other suitable polymer-hardening precursor materials include silicon carbide, carbon and silicon nitride. Thus, the invention is more generally directed to heating a polymer-hardening precursor material of the type including silicon to at least a higher temperature range (above the



(12)

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## (54) Plasma reactor with heated source of a polymer-hardening precursor material

(57) A general method of the invention is to provide a polymer-hardening precursor piece (such as silicon, carbon, silicon carbide or silicon nitride, but preferably silicon) within the reactor chamber during an etch process with a fluoro-carbon or fluoro-hydrocarbon gas, and to heat the polymer-hardening precursor piece above the polymerization temperature sufficiently to achieve a

desired increase in oxide-to-silicon etch selectivity. Generally, this polymer-hardening precursor or silicon piece may be an integral part of the reactor chamber walls and/or ceiling or a separate, expendable and quickly removable piece, and the heating/cooling apparatus may be of any suitable type including apparatus which conductively or remotely heats the silicon piece.

## Description

The invention is related to a plasma reactor for processing a workpiece such as a semiconductor wafer with a process employing an etch selectivity-enhancing precursor material such as polymer precursor gases.

High density RF plasma reactors for etching contact openings through silicon dioxide layers to underlying polysilicon conductor layers and/or to the silicon substrate of a semiconductor wafer are disclosed in the above-referenced application by Collins et al. Ideally, such a reactor carries out an etch process which quickly etches the overlying silicon dioxide layer wherever a contact opening is to be formed, but stops wherever and as soon as the underlying polysilicon or silicon material (or other non-oxygen-containing material such as silicon nitride) is exposed, so that the process has a high oxide-to-silicon etch selectivity. Such reactors typically include a vacuum chamber, a wafer support within the chamber, process gas flow inlets to the chamber, a plasma source coil adjacent the chamber connected to an RF power source usually furnishing plasma source power and another RF power source connected to the wafer support usually to furnish plasma bias power. For a silicon oxide etch process, a process gas including an etchant such as a fluorine-containing substance is introduced into the chamber. The fluorine in the process gas freely dissociates under typical conditions so much that the etch process attacks not only the silicon oxide layer through which contact openings are to be etched, but also attacks the underlying polysilicon or silicon material as soon as it is exposed by the etch process. Thus, a typical etch process carried out by such a reactor is not the ideal process desired and has a lower oxide-to-silicon etch selectivity. As employed in this specification, the term "etch selectivity" refers to the ratio between the etch rates of two different materials, such as silicon dioxide and silicon (either crystalline silicon or polycrystalline silicon hereinafter referred to as "polysilicon"). A low etch selectivity can cause punch through. In etching shallow contact openings to intermediate polysilicon layers while simultaneously etching deep contact openings to the underlying silicon substrate, the etch process first reaches and will punch through the intermediate polysilicon layer before reaching the silicon substrate. A very high oxide-to-silicon etch selectivity is necessary to prevent the punchthrough, depending upon the ratio between the depths of the silicon substrate and the intermediate polysilicon layer through the silicon oxide. For example, if (a) the deep contact opening through the oxide to the substrate is 1.0 micron deep and is to be 50% over-etched, (b) the intermediate polysilicon layer is 0.4 microns deep (below the top of the oxide layer) and (c) if not more than 0.01 microns of the intermediate polysilicon layer are to be removed (to avoid punch-through), then an oxide-to-silicon etch selectivity of at least 110:1 is required.

It is known that oxide-to-silicon etch selectivity is en-

hanced by a polymer film which forms more readily over silicon and polysilicon or other non-oxygen-containing layers than over silicon dioxide or other oxygen-containing layers. In order to form such a selectivity-enhancing polymer film, the fluorine-containing substance in the process gas is a fluoro-carbon or a fluoro-hydrocarbon. Some of the fluorine in the process gas is consumed in chemically etching the silicon dioxide layer on the wafer. Another portion of the fluorine reacts with other species including carbon contained in the process gas to form a polymer on the surface of the wafer. This polymer forms more rapidly and strongly on any exposed silicon and polysilicon surfaces (or other non-oxygen-containing surfaces) than on silicon dioxide (or other oxygen-containing surfaces), thus protecting the silicon and polysilicon from the etchant and enhancing etch selectivity. Etch selectivity is further improved by improving the strength of the polymer formed on polysilicon surfaces. The polymer is strengthened by increasing the proportion of carbon in the polymer relative to fluorine, which can be accomplished by decreasing the amount of free fluorine in the plasma. For this purpose, a fluorine scavenger, such as a silicon piece, can be provided in the reactor chamber and heated to avoid being covered with polymer and additionally to permit silicon ions, radicals and/or neutral species to be removed therefrom and taken into the plasma. The silicon atoms removed from the scavenger combine with some of the free fluorine in the plasma, thereby reducing the amount of fluorine available to polymerize and increasing the proportion of carbon in the polymer formed on the wafer.

While the use of a fluorine scavenger such as a heated silicon piece inside the reactor chamber enhances etch selectivity by strengthening the polymer formed on the wafer, even the etch selectivity so enhanced can be relatively inadequate for a particular application such as the simultaneous etching of contact holes of very different depths. Therefore, it would be desirable to increase the polymer strength beyond that achieved by the improved scavenging technique described above.

Another problem is that the rate of removal of silicon from the scavenger piece required to achieve a substantial increase in polymer strength is so great that the silicon piece is rapidly consumed and the consequent need for its replacement exacts a price in loss of productivity and increased cost. Typically the scavenger piece is a piece of silicon in the reactor chamber ceiling or wall or a piece of silicon near the reactor chamber ceiling. The rate of removal of silicon therefrom is enhanced by applying an RF bias potential to the silicon piece while its temperature is carefully controlled to a prevent polymer deposition thereon and to control the rate of silicon removal therefrom. As disclosed in the above-referenced U.S. application Serial No. 08/543,067, silicon is added into the plasma by a combination of applied RF bias and heating of the scavenger piece. The temperature control apparatus is integrated with the silicon piece so that replacement of the silicon



European Patent  
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## EUROPEAN SEARCH REPORT

Application Number  
EP 97 30 3170

## DOCUMENTS CONSIDERED TO BE RELEVANT

Ref.-no./v	Citation or document with indication, where appropriate, of relevant passages	Relevant Date (m)	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	PATENT ABSTRACTS OF JAPAN vol. 006, no. 119 (E-116), 3 July 1982 & JP 57 045927 A (FUJITSU LTD), 16 March 1982. * abstract *	31.32.49	
A	DATABASE WPI Section EI, Week 9609 Derwent Publications Ltd., London, GB: Class S03, AN 96-082046 XP002047814 & JP 07 333 065 A (HAFURISAKO Y) . 22 December 1995 * abstract *	36.51. 53.64.65	
A	US 5 249 251 A (EGALON CLAUDIO O ET AL) * column 1, line 19 - line 22 *	52	
A	US 5 276 693 A (LONG GARY ET AL) * abstract *	60	
	* column 1, line 12 - line 20 *		TECHNICAL FIELDS SEARCHED (Int.Cl.6)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	21 November 1997	Capostagno, E
CATEGORFY OF CITED DOCUMENTS		
X particularly relevant if taken alone	T theory or principle underlying the invention	
Y particularly relevant if combined with another document of the same category	E earlier patent document, but published on or after the filing date	
A technological background	D document cited in the application	
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P intermediate document	S member of the same patent family, corresponding document	

